IMPERIAL COLLEGE LONDON

(University of London)

Department of Earth Science and Engineering

Centre for Petroleum Studies

The Development of A New Upscaling Workflow for PETRONAS Full Field Review (FFR) Projects

By

Nurul Azrin Amiruddin

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DECLARATION OF OWN WORK

I declare that this thesis The Development of A New Upscaling Workflow for PETRONAS Full Field Review (FFR) Projects is entirely my work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

Signature : .....

Name of student : Nurul Azrin Amiruddin

Name of supervisors : Dr. Matthew Jackson (Imperial College)

Dr. Nasir Darman (PETRONAS)

ABSTRACT

Nowadays, the awareness amongst the reservoir engineers of proper practice in upscaling a static model which contains millions of gridblocks into a coarser dynamic model has increased significantly. In this report, a new upscaling workflow is developed for the PETRONAS full field review (FFR) team to assist them in constructing a reliable dynamic model to meet the objective(s) of their project. In order to come up with a helpful upscaling workflow, a few upgridding and upscaling methods are being tested to assess the performance of each method on a real field model (Field 'X'). The upgridding methods involved for assessment include the simple uniform layering method, the variance in saturation method and the Stern and Dawson method. Whereas, the upscaling methods involved include the rock curve method, Vertical Equilibrium (VE) method, Kyte and Berry (KB) method, Stone method, Hewett and Archer (HA) method and Transmissibility-weighted (TW) method. From the findings on the upgridding activities, it can be summarised that the variance in saturation method is the most suitable method to be used for Field X, where the layering can be further coarsened probably up to 20-layers scheme with that method. It is also observed that the Stern and Dawson method does not perform as good as the variance in saturation method and the uniform layers method happens to work surprisingly well for the Field X model. From these upscaling activities, it can be summarised that the VE method does not work for Field X, the KB method performed worse than the Stone method and the TW and HA methods have the same results with the rock curve method. In conclusion, the objective of developing a new upscaling workflow for the PETRONAS FFR team or other simulation project is met mainly referring to the literature reviews and supported by some of the findings of this paper.

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CHAPTER 1: INTRODUCTION

1.1 Background

A full field review (FFR) is conducted to evaluate a mature oil and gas reservoir to maximise its recovery. One of the main components in the review is the construction of the dynamic model which will be used for the reservoir simulation process. Simulation of the reservoir model acts as one of the most important tools to optimize the capital investment and predict the suitable recovery mechanism, which minimize the operational risks. Thus, a reliable reservoir simulation model is crucial and it should preserve the heterogeneities and the flow properties of the geological model.

The modern reservoir characterization incorporated detailed reservoir description with millions of cells in the fine-grid geological model. In general, the incorporation of this small-scale heterogeneity in fluid flow simulation is an essential and compulsory step in order to get a reliable prediction. Fluid flow simulations of such big models exceed the conventional simulator computational capabilities and very complex to deal with. In order to run the simulation effectively, these fine-grid models need to be scaled up into coarse-grid models while still preserving the properties and heterogeneities of the fine-grid reservoir models.

Once the model has been upgridded by redefining the number of layers and the geometry of the grid blocks, the permeabilities, porosities, relative permeabilities and the capillary pressures of the grids are assigned accordingly. The process may be a simple averaging of the grid or might involve the application of full dynamic upscaling method that require the generation of pseudo functions in the context of multiphase flow. Figure 1-1 below illustrates the upgridding and upscaling of a fine-grid model into a coarse-grid model.

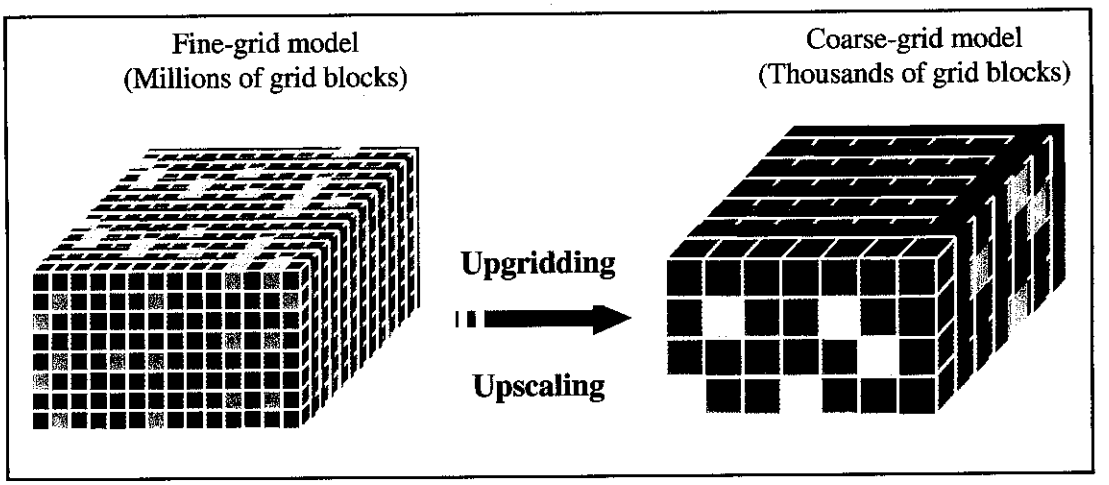

Figure 1-1: Illustration of upgridding and upscaling of a fine-grid model into a coarse-grid model

Several upgridding and upscaling techniques have been developed and described in the literature. In this report, some of those techniques are tested and discussed in the following chapters, which focus on the errors associated with each technique compared to the fine-grid model. The results are then analysed to develop a new upscaling workflow for the FFR team. The proposed upscaling workflow will work as a guideline to assist the FFR team in upscaling their geological model effectively, thus producing a reliable dynamic model to meet the team's objective(s) accordingly.

In this study, a real field is being used for the study to evaluate the reliability of the different upgridding and upscaling methods that has been developed in literatures. However, the identity of the field is confidential and is disclosed to accommodate the interest of PETRONAS Research and its clients. The Field X model (not the real name), which is located in the Malay Basin is being used for the study. For the upgridding and upscaling activities, only the cross sections of the model are involved for evaluation (error analysis).

1.2 Objective

The main objective of the project is to develop a new upscaling workflow for PETRONAS Full Field Review (FFR) projects and any reservoir simulation projects.

1.3 Scope of Work

This study focuses on the following scope of work:

a. Testing of the different methods for upgridding a fine-grid (geological) model to determine the optimum layering scheme of the coarse-grid (simulation) model.

b. Testing of the different methods for upscaling the dynamic properties of the fine-grid model to be used in the coarse-grid model.

c. Quantifying the error associated with each methods compared to the fine-grid model in terms of its oil production, water-cut and pressure profile.

d. Developing the upscaling workflow suitable for any full field review (FFR) project as part of its dynamic modelling process.

CHAPTER 2: LITERATURE REVIEW

This chapter describes the terminology and theoretical background of the main activities involved in the study, especially on upgridding and upscaling. The milestone of the subjects and the detailed summary on the literatures are summarised in Appendix A.

2.1 Upgridding

Upgridding involves systematic ways to determine the most suitable and optimized configuration of the coarse grid model. In other words, upgridding requires a certain strategy to produce a coarse-grid model that is suitable for running in the simulation mode and maintain the accuracy as if it is the fine-grid model quality. It is necessary to refine the grid in certain parts of the reservoir to obtain desired accuracy between the fine-grid and the coarse-grid model such as local refinement around the wells and coarser grid over aquifers as well as large gas caps where pressure and saturations change slowly (Aziz and Settari, 1990).

Generally, an irregular grid is advantageous in cross-sectional and 3-D simulations of stratified reservoirs where the vertical grid is chosen according to reservoir stratification (Aziz and Settari, 1990). The reservoir engineer would decide the number of layers needed, the location of simulation boundaries, as well as the number and dimensions of each grid block in the areal direction (Stern and Dawson, 1999). Nowadays, a number of methods are available to help the engineer determine the optimal number of layer of the coarse-grid model where some of these methods are discussed next.

2.1.1 Simple Uniform Layer Method

Generally, the simple uniform layer method allows the user to do specify the number of layers desired for their coarse-grid model and then determine the optimum layering scheme after considering a few layering combination. The method simply coarsened the fine-grid layers into the number of layers specified and the thickness of the coarsened grids are averaged uniformly through-out the entire model. Once the coarse-grid model simulation results match the fine-grid model simulation results, the optimum number of layers has been established. This method is too simple and the heterogeneities of the fine-grid model might be lost due to over simplification if it happens that the heterogeneities were averaged into a single coarsened grid (Aziz and Settari, 1990).

2.1.2 Stern and Dawson Method

Stern and Dawson (1999) suggested an iterative layer optimisation process that involved the use of objective function (breakthrough-time or flux) and calculation of sweep efficiency of the coarse and fine-grid flow property. The variance of the calculated parameters is minimised to preserve and capture the heterogeneity of the fine-grid model. The iteration process starts by combining layers of the fine-grid model that produces the smallest possible difference between the coarse and the fine-grid model properties. The coarsening process can then be terminated based on a maximum error in swept volume, which means the coarse-grid model no longer properly captures the vertical heterogeneity of the fine-grid model.

The breakthrough-time objective function can be defined as the difference in single-phase breakthrough-time required between the fine-grid and coarse-grid models, normalised to the fine-grid breakthrough-time as shown by the equation below:

$$F_k^{c,r} = \left[\left(\frac{\tau_{kf} - \tau_{\lambda c}}{\tau_{kf}} \right)^2 \right]^{c,r}$$

$$O_{HET} = \sum_{c,r,k} F_k^{c,r}$$

where τ_{kf} is breakthrough-time in fine-grid layer k, $\tau_{\lambda c}$ is breakthrough-time in coarse grid layer λ, c is coarse-grid model, c,r is column and row in the fine-grid model, $F_k^{c,r}$ is the objective function for the fine-grid layer k in column c and row r, and O_{HET} is the sum of the objective functions over all fine-grid cells.

The flux objective function can be defined as the difference between fine-grid and coarse-grid flux (flow rate relative to the pore volume) and governed by the following equation:

$$F_k^{c,r} = abs\left[\left(\left\{\frac{Q}{PV}\right\}_{\lambda c} - \left\{\frac{Q}{PV}\right\}_{kf}\right)\right]^{c,r}$$

where Q is total volumetric flow rate and PV is pore volume of a layer.

The calculation technique of the swept volume is over-simplified by assuming the gravity and capillary pressure to be zero and cross flow between layers, kv=0. This is the disadvantage of the technique as it will not represent the actual flow behaviour that may be encountered in the reservoir.

2.1.3 Variance in Saturation Method

Darman et. al (2000) suggested a method that differs from conventional coarsening schemes where it takes into account not only the static properties of the fine-grid models but also the dynamic properties of the fine-grid simulation runs such as the flood pattern, pressure and saturation distribution. For a gas injection case, the idea of the coarsening method is to identify regions of the fine-grid models where there is low variability of gas saturation and to take such regions as the corresponding coarse grid blocks.

The average saturation equation used is expressed in terms of the moments as given by:

$$\phi\frac{\partial\bar{S}}{\partial t}+\nabla\cdot\left\{f_s(\bar{S})\overline{v'S'}\right\}-\frac{g\Delta\rho}{\mu_o}\nabla\cdot\left\{\left(\bar{k}\eta(\bar{S})+\frac{1}{2}\eta_{ss}(\bar{S})\overline{kS'S'}+\eta_s(\bar{S})\overline{k''S'}\right)\cdot i_z\right\}=0$$

where S is the gas saturation, $f(S)$ is the gas fractional flow, η is $k_{ro}f$, t is time, v is total Darcy velocity, $\Delta\rho=\rho_g-\rho_o$(densities), g is gravitational acceleration (z-direction), μ_o is oil viscousity, k is the local permeability tensor, i_z is the z-unit vector, k_{ro} and k_{rg} are oil and gas relative permeabilities and f_s, η_s, f_{ss} and η_{ss} are the first and second derivatives of f and η with respect to S. When water flooding is considered instead of gas injection, then all the *gas* term should be replaced by *water*.

If the higher moment terms are neglected by the use of rock curves on the coarse scale, the equation can determine the error that correlates with the magnitudes of the neglected terms. Table 2-1 gives the appropriate moments when different fluid forces act.

Forces	Fluctuating Moments
Viscous	$\overline{S'S'}$ and $\overline{v'S'}$
Gravity	$\overline{S'S'}$ and $\overline{k'S'}$
Capillary	$\overline{S'S'}$, $\overline{S'\cdot\frac{\partial S'}{\partial x}}$ **and** $\overline{k'\cdot\frac{\partial S'}{\partial x}}$

Table 2-1: Appropriate fluctuating moments for each of the fluid force balance regimes.

Other upgridding technique has also been suggested by other author such as Durlofsky (1997) but the techniques described in this section are specifically tested for the study.

2.2 Upscaling

Upscaling is the process of using information at one length scale in order to compute equivalent or effective properties at a larger scale. Single-phase upscaling is relatively easy to apply, and is routinely carried out. On the other hand, two-phase upscaling is very difficult to apply because the results are likely to depend on flow rate and direction, especially on the well configuration.

All dynamic pseudo generation methods involve performing and then using the results of fine grid flow simulations. Basically, there are two major steps in generating dynamic pseudo functions. Firstly, all the single-phase fluid flow properties such as porosity (pore volume) and absolute permeability (transmissibility) must be averaged. For porosity (pore volume) averaging, the process is very straightforward because only the total pore volume needs to be conserved. On the other hand, permeability (transmissibility) averaging can be obtained using methods as simple as applying the arithmetic or harmonic averages through more sophisticated methods involving solving Laplace's equation. Guzman *et al.* (1994) noted that the accuracy of the permeability averaging was increased by solving Laplace's equation compared to carrying out simple harmonic or arithmetic averaging. Generally, the scaleup of these single-phase properties is not an issue in generating pseudo functions since both of them are only functions of the porosity/permeability distribution and coarse grid geometry alone (Hewett 1997).

The dynamic properties require the use of pseudo-functions to determine the relative permeabilities and capillary pressures of the coarse-grid model which are derived from the various upscaling methods. The methods are the vertical equilibrium (VE) method and the dynamic pseudo-functions technique such as Kyte and Berry (KB) method, Stone method, Hewett and Archer (HA) method and transmissibility-weighted (TW) method (originally referred to transmissibility-potential-weighted (TPW)) method. Each of these methods performed efficiently at different flow

conditions and the user need to use them accordingly as being discussed by Barker and Dupouy (1999), Coll et. al (1998), Taggart et. al (1995) and others.

Generally, when successfully applied, the pseudo functions produced in a dynamic upscaling method will incorporate the interaction between small scale multi-phase fluid flow and heterogeneity, as well as correcting for the numerical dispersion. However, pseudo functions can be sensitive to boundary conditions which results in lack of robustness in the coarse-scale model (Darman et. al, 1999 and 2000).

2.2.1 Rock Curve Method

The relative permeability and capillary pressure of the coarse-grid model are determined using the correlations obtained from core data for each facies type. The curves of the fine-grid cells in the coarse-grid cell are averaged, normalised and denormalised for the coarse-grid accordingly. This method could be used for single phase or multiphase upscaling and popularly used by most reservoir engineers due to its simplicity but the accuracy of the method is not guaranteed (Aziz and Settari, 1990).

2.2.2 Vertical Equilibrium (VE) Method

Developed by Coats et. al (1967), the VE method is one of the earliest pseudo-isation techniques available. The use of this pseudo concept is motivated by the need to simulate 3D two-phase flow with a 2D reservoir simulator in which vertical effects are included. Viscous forces must be negligible in the vertical direction. Also, the reservoir must have sufficient vertical permeability to allow fluids to segregate completely and instantaneously. The main condition for VE is achieved when the viscous to gravity ratio is low enough that the vertical potential gradient of each fluid phase is essentially zero.

$$\frac{\partial \Phi_p}{\partial z} = 0.0$$

where p = oil, water or gas. From the equation above and the definition of capillary pressure, we can deduce that:

$$P_c(x, y, z) = P_c(x, y, z_{ref}) - \int_{z_{ref}}^{z} (\rho_o - \rho_g) g_z .dz$$

where $P_c(x,y,z_{ref})$ is the capillary pressure for a given point (x,y) on a reference surface z_{ref}. z_{ref} is usually taken at the oil-water contact or mid-point of the reservoir. The above two equations apply to all points within the three-dimensional medium. Thus, by adopting these equations, 3D fluid flow models can be represented by only 2D areal model with properties variation in the vertical direction are accounted for (Coats et. al, 1971).

Dake (1978) defined the favorable conditions for the VE methods to be applied as follows:

- *small reservoir thickness*
- *low fluid viscosities*
- *low injection rates*
- *low lateral velocities*
- *large vertical permeabilities*
- *high gravity and/or capillary forces.*

2.2.3 Kyte and Berry (KB) Method

The original Kyte and Berry method calculates the pseudo functions from two-dimensional, vertical cross-section runs (Kyte and Berry, 1975). This method ensures that no additional numerical dispersion will occur in the areal model, regardless of the areal computing block lengths. This method attempts to overcome the assumption of equal potential differences in all fine and coarse grid layers by estimating coarse grid pressures from fine grid pressures and using them to calculate the coarse grid

potential differences, which are then used to calculate pseudo relative permeability from Darcy's Law (Stone, 1971). Kyte and Berry estimate the coarse grid pressures ($\overline{P_p}$) by averaging the fine grid pressures and use the product of phase relative permeability (kr_p) times total permeability (k_j) times layer thickness (dz_j) as a weighting factor as shown:

$$\overline{P_p} = \frac{\sum_{j=1}^{n}\left[k_j \cdot kr_{p_j} \cdot dz_j\left(P_{p_j} - g \cdot \rho_p \cdot (D_k - D)\right)\right]_{i=n-2}}{\sum_{j=1}^{n}\left[k_j \cdot kr_{p_j} \cdot dz_j\right]_{i=n-2}}$$

In the Kyte and Berry method, the flow rate, q_p, of phase p in the fine and the coarse grid blocks was matched by summing the respective phase fluid flow rates over the fine grid blocks located at the coarse grid block boundary (q_{pk}) as given by:

$$\overline{q_p} = \sum_{k=1}^{n}\left[q_{pk}\right]_{i=n}$$

Note that the potential gradient was found by first taking the average potentials in the coarse blocks and then taking the difference to calculate the $\overline{\Delta\Phi_p}$. This phase potential difference was then used to solve Darcy's Law in order to obtain the (pseudo) relative permeability function $\left(\overline{kr_p}\right)$ for each fluid phase in the coarse grid blocks as shown as follows:

$$\overline{kr_p} = \frac{-\overline{\mu_p}.\overline{q_p}.\Delta X}{\Delta Z.\Delta Y.\overline{kx}.\overline{\Delta\Phi_p}}$$

Where $\overline{\mu_p}$, $\overline{q_p}$ and $\overline{\Delta\Phi_p}$ are the average phase viscosity, total phase flow rate and fluid potential difference of phase p respectively; $\Delta X, \Delta Y$ and ΔZ are the coarse grid-block dimensions in the x, y and z-directions.

The pseudo potential difference, $\overline{\Delta\Phi_p}$ was given by the following equation:

$$\overline{\Delta\Phi_p} = \overline{\Delta P_p} - g.\rho_p.\Delta D$$

Kyte and Berry method uses the product of phase relative permeability times the absolute permeability times layer thickness as a weighting factor to average the respective fluid pressures. To be meaningful, the derived pseudo relative permeability must be related to the averaged saturation in the coarse block. In this case, the saturation, $\overline{S_p}$ was averaged using pore volume weighting over the entire fine grid blocks (PV_{ik}) to give the following value in a coarse gridblock where S_{pik} is the phase saturation over the entire fine grid blocks:

$$\overline{S_p} = \frac{\sum_{k=1}^{n}\sum_{i=1}^{n} S_{pik}.PV_{ik}}{\sum_{k=1}^{n}\sum_{i=1}^{n} PV_{ik}}$$

By summing the respective flow rate of each fluid only at the downstream boundary grid blocks of the coarse grid while averaging the saturation over the entire coarse grid block, numerical dispersion is minimized. This is one of the most important ideas that Kyte and Berry introduced in their method, as the actual title of their paper implies.

2.2.4 Stone Method

The Stone method (Stone, 1991) avoids the need to know potential differences as being used in Darcy's Law by using a fractional flow formulation that requires (i) the averaged fractional flow, $\overline{f_p}$ and (ii) the averaged total pseudo mobility, $\overline{\lambda_t}$. These two quantities were found using the following equations:

$$\overline{f_p} = \frac{\overline{q_p}}{\overline{q_t}} = \frac{\sum_{k=1}^{n}[q_t.f_p]_{i=n}}{\sum_{k=1}^{n}[q_t]_{i=n}}$$

$$\overline{\lambda_t} = \frac{\sum_{k=1}^{n} [T_{xk} \cdot \lambda_{tk}]_{i=n}}{\sum_{k=1}^{n} [T_{xk}]_{i=n}}$$

Where $T_x = \frac{kA}{\Delta x}$ is the transmissibility, a function of permeability and the grid block geometry whereas $\overline{q_p}$ and $\overline{q_t}$ are the average phase and total flow respectively.

From the above, the Stone pseudo relative permeability for phase p was then calculated using equation below where $\overline{\mu_p}$ is the average phase viscosity:

$$\overline{k_{rp}} = \overline{\mu_p} \cdot \overline{f_p} \cdot \overline{\lambda_t}$$

The equations used show that to make the coarse grid flow of a phase equal to the sum of its fine grid flows, it is only necessary to make the coarse grid fractional flow a total flow rate weighted average of the fine grid fractions. Then, the corresponding saturations are calculated as in the Kyte and Berry method, which provides the Stone method with the ability to control numerical dispersion and consider fine scale heterogeneity in a coarse grid simulation. The Stone method is rigorous for all flow rates, even for non-communicating layers where the viscous to gravity ration is infinite. However, Barker and Fayers stated that the method can give poor results in cases with significant gravity (or capillary pressure) effects or with significant variations in total mobility (Barker and Fayers, 1994).

2.2.5 Hewett and Archer (HA) Method

Hewett and Archer introduced the unambiguous rules for computing effective flow properties for coarse-grid simulations based on the results of fine-grid simulations. The rules are based on the concept of computing integrated phase mobilities in streamtube segments whose geometry is defined by the fine-grid cells at the coarse-grid block outlet face (Hewett and Archer, 1997). One streamtube is defined for each

of the fine grid cells comprising the coarse grid block outlet face and each streamtube consists of all streamlines passing through one fine grid block outlet face. These streamtubes are based on the total volumetric flowrate, since this is the only conserved quantity in unsteady multi-phase flow. The individual phase mobilities for each of these streamtubes are then calculated in the segments which are between the iso-potential lines running through the centers of the coarse grid block n and the one next to it, (n+1).

Hewett and Archer introduce capillary pressure into their upscaling procedure by the introduction of an effective capillary pressure defined by associating the capillary pressures at the coarse-grid block centers with the average saturations of the coarse-grid blocks. The effect of gravity is tackled by the addition of the conventional gravity term based on the actual phase density differences and the difference in elevation of the coarse-grid block centres.

However in the real calculation of the pseudo functions, they never actually calculate the geometry of these streamtubes or define the location of the iso-potential lines except at the coarse grid blocks centers. Indeed, the HA method simply takes the potential in the fine grid block located at the center of the coarse grid block. Thus, what are required from the fine grid solutions are only:

i. the phase fluxes from each of the fine grid cells comprising the outlet face of the coarse grid blocks,

ii. the oil phase potentials in the fine grid cells containing the coarse grid block centers,

iii. the capillary pressure in the same fine grid cells,

iv. the elevation difference in the coarse grid cell centers, and

v. the porosity weighted averaged saturation of the coarse grid blocks.

In this method, the oil potential differences $\Delta\Phi_o$ were simply taken as the difference in oil phase potential of the fine grid cell located at the coarse grid centers. The gas potential difference $\Delta\Phi_g$ was calculated using below:

$$\overline{\Delta\Phi_g} = \overline{\Delta\Phi_o} + \overline{\Delta P_c} - \Delta\rho g\,\overline{\Delta h}$$

where $\overline{\Delta P_c}$ is the difference in capillary pressure between grid block n and n+1, and $\overline{\Delta h}$ is the difference in elevation between these two grid blocks. Both of these values are taken at the fine grid block located at the center of the coarse grid blocks.

This method uses Darcy's equation to obtain the pseudo relative permeability:

$$\overline{q_o} = \frac{\overline{T_x}\,\overline{k_{ro}}}{\overline{\mu_o}}\cdot\overline{\Delta\Phi_o} \qquad \overline{q_g} = \frac{\overline{T_x}\,\overline{k_{rg}}}{\overline{\mu_g}}\cdot\left[\overline{\Delta\Phi_o} + \overline{\Delta P_c} - \Delta\rho g\,\overline{\Delta h}\right]$$

where overbar indicates the averaged properties for the coarse grid blocks and the nomenclatures used have been defined in the earlier sections.

2.2.6 Transmissibility-weighted (TW) Method

The approach of TW method follows exactly the same as the KB method except in the averaging the fluid potential difference at the coarse-grid level (Darman et. al, 1999). The flow rates of individual fluid phases in the fine and the coarse-grid blocks were matched by summing the respective phase flow rates over the fine-grid blocks located at the coarse-grid block boundary. The derived pseudo relative permeability must be related to the average saturation in the coarse-grid block where the saturation was averaged using pore volume weighting over the fine-grid blocks. The pseudo relative permeability for each fluid phase in the coarse grid block is given by:

$$\overline{k_{rp}} = \frac{-\overline{\mu_p}\cdot\overline{q_p}\cdot\Delta X}{\Delta Y\cdot\Delta Z\cdot\overline{k_x}\cdot\overline{\Delta\Phi_p}}$$

Where $\overline{\mu_p}$, $\overline{q_p}$ and $\overline{\Delta\Phi_p}$ are the average phase viscosity, total phase flow rate and fluid potential difference of phase p respectively; $\Delta X, \Delta Y$ and ΔZ are the coarse grid-block dimensions in the x, y and z-directions. The transmissibility is a function of permeability and the grid block geometry, $T_x = \frac{kA}{\Delta x}$ and the average potential difference is defined as $\overline{\Delta\Phi_p} = \frac{\sum_{j=1}^{n}\left[T_{xj}\cdot\Delta\Phi_{p_j}\right]_{t=n-2}}{\sum_{j=1}^{n}\left[T_{xj}\right]_{t=n-2}}$.

In addition, the use of transmissibility as the weighting factor in averaging the fluid potential gradients is more appropriate compared to the use of relative permeability times layer thickness times absolute permeability as in the Kyte and Berry method. Darman et. al showed that the TW method gives more accurate results in applying pseudo functions where gravity effects are significant such as in immiscible gas injection, compared to the earlier published methods.

All of the above theoretical backgrounds on each method are embedded in the software used for the study namely the PRSS P-Upscale and Eclipse-Pseudo. The knowledge on each method is crucial to ensure the understanding of the results obtained from the software applications for analysis.

CHAPTER 3: FIELD 'X' MODEL DESCRIPTION

As mentioned in Section 1.1, a real field is being used for the study to evaluate the reliability of the different upgridding and upscaling methods that has been developed in literatures. The model being used is the Field X model which has been developed by its FFR team. In order to further understand the static and dynamic attributes of the field some overviews of the work done on the geological and simulation models are discussed in the following sections.

3.1 Geological Model

The static (geological) model of Field X contains ~ 1.8 million grid cells $(169\times96\times116)$, which was constructed in Roxar's RMS software. Laterally, the static model covers an area measured $8.5km\times4.8km$ $(5.3miles\times3.0miles)$. There are 37 wells within the modelled area.

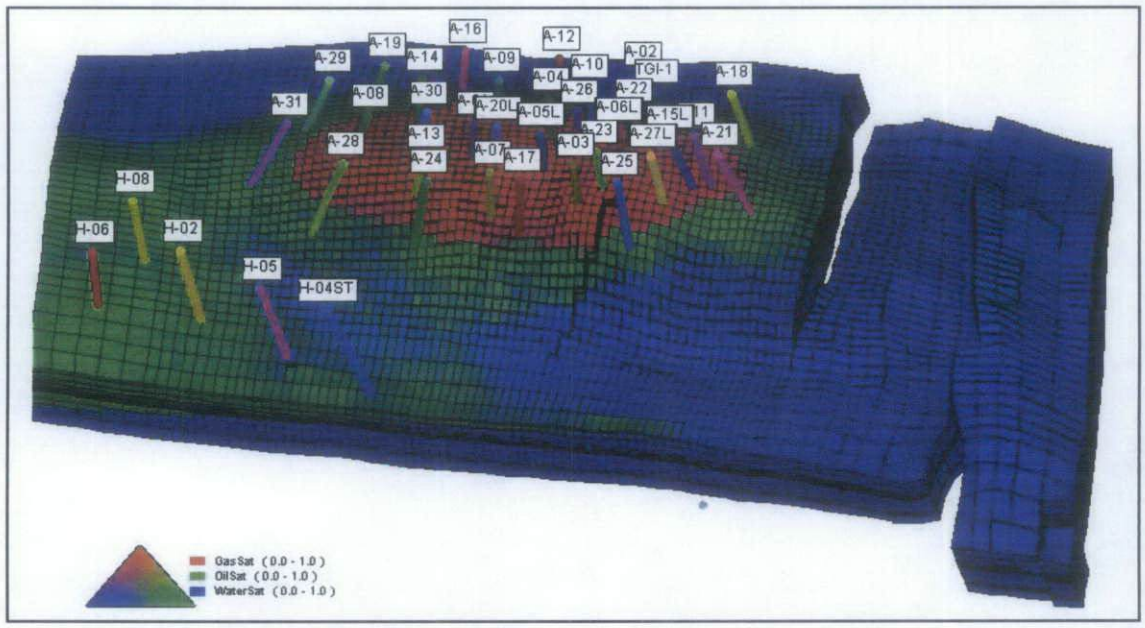

Figure 3-1: Static model of Field X.

The geologist interpreted that the facies model follows an estuarine conceptual model for a tidal to sub-tidal complex deposited in a confined basin at the mouth of a major river. The lower part of the sand reservoir is interpreted as prograding tidal sand bars/ sand flats. Throughout the sand interval, there are pulses of relative sea-level rise where transgressive medium to low-energy sub-tidal sediments were deposited. These intervals are extensive and are likely to act as permeability baffles within the reservoir. Five facies were modelled namely tidal sand bar (dominant facies), tidal sand flat, high energy sub-tidal, mod energy sub-tidal and low energy sub-tidal. The tidal sand bars together with the background tidal flats which comprise marginally poorer reservoir quality sandstones, a well connected and extensive sandstone sheet is formed.

Fifteen faults were modelled and have normal displacements with steep dip angles. The displacements are sufficient to affect transmissibility via sand juxtaposition or shale gouge within the reservoir. Stochastic conditional simulation was chosen to model the petrophysical attributes, which were distributed through out the model volume. The base case volumetric calculation of the model results in 220 MMbbls of STOIIP and 156Bcf of GIIP. During the construction of the geo-cellular model, several quality check activities were conducted including 3D visualisation techniques and cross-sections, 'grid quality control' utility in RMS and cross-checking the blocked data vs. raw well statistics.

3.2 Simulation Model

The FFR team constructed the simulation model by first establishing the vertical grid design of the model using PRSS's P-Upscale application, which was used to determine the optimum layering scheme. Two cross-sectional models were constructed to enable reasonable simulation run time of the fine-grid model when comparing with the coarse-grid model. Water and gas injection scenarios were simulated for the different layering configuration runs. Coarse grids ranging from 14 layers to 35 layers were built to check their ability in reproducing results of the fine-

grid simulations using the P-Upscale application with the variance in saturation technique.

Finally, it was observed that the 22-layer coarse-grid model generated results that are comparable to those from simulations with finer grid cases. Laterally, 85x40 grid was being used for the three-dimensional grid after considering the wells spacing, elimination of aquifer grid cells and honouring the faults.

The static model properties (NTG, permeability, porosity, crititical water saturation (Swc) and residual oil saturation (Sor)) were upscaled using Schlumberger's FloGrid application which applies simple arithmetic averaging, linear boundary conditions, NTG weighted averaging and net pore volume averaging. The team believed that no pseudo-functions were necessary for the upscaling process as the upscaling of the absolute permeability is sufficient to reasonably preserved the static model properties in the coarse-grid model.

A regional aquifer model was also prepared to understand the overall depletion process during the development of a neighbouring Field S (not the real name) which happens 7 years later than that of Field X. The aquifer model essentially covers the combined Field S and Field X area in order to evaluate the interference of Field S development on the Field X recovery process. Thus, the effects of Field S wells production activities were accounted for and incorporated into the dynamic model alongside with the Field X wells.

The model was then calibrated by history matching using the 22-year production history data obtained from each well to ensure its reliability in predicting the future performance of the reservoir.

3.3 Reservoir Properties

For simplification, a single relative permeability and capillary pressure curve is being used for the model which is shown in Figure 3.2 below where it is assumed only a single rock type is present:

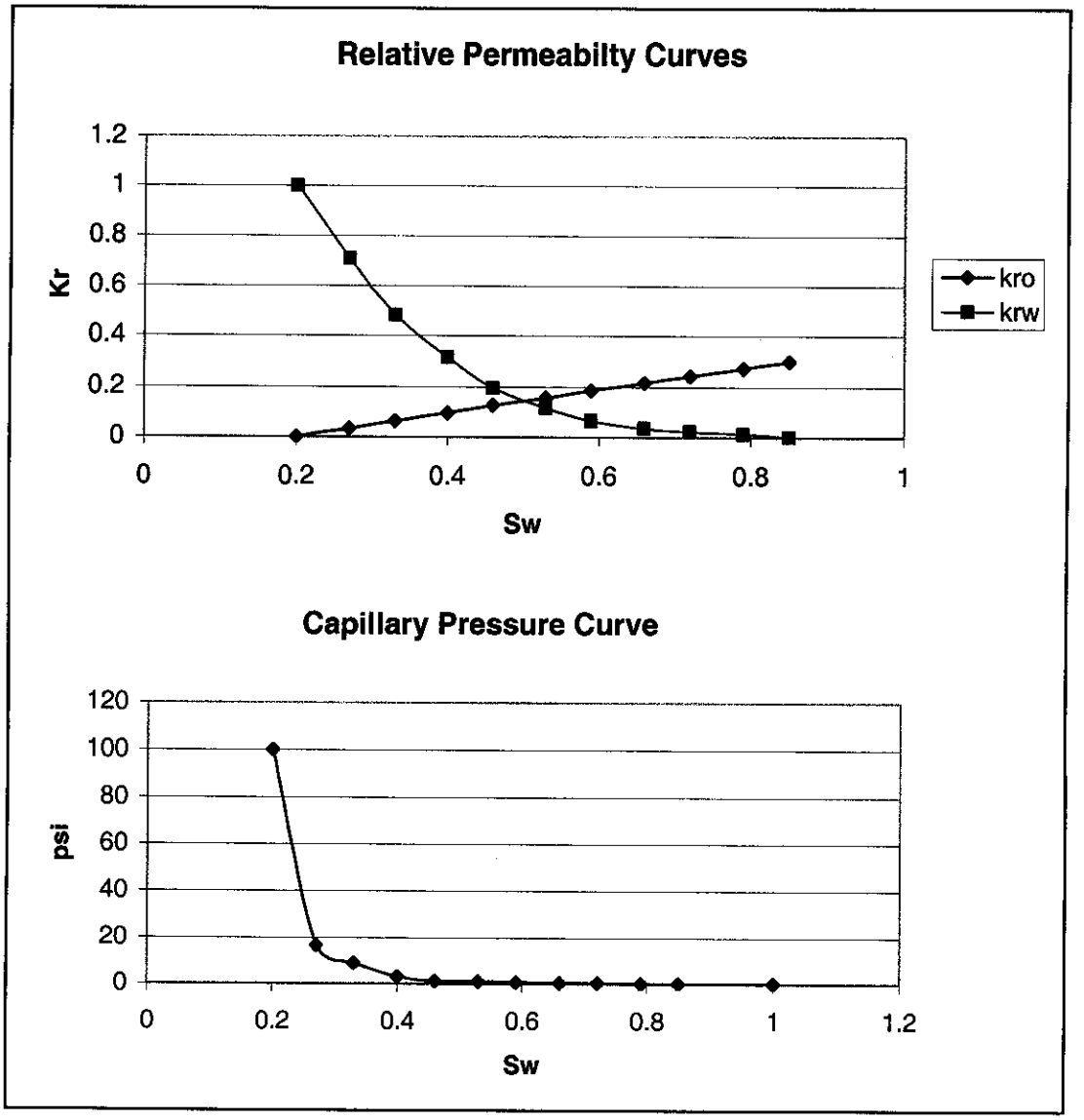

Figure 3-2: Relative permeability and capillary pressure curve for the Field X model.

The permeability of the reservoir ranges between 2mD to 5000mD and porosity of 6% to 33%.

The fluid properties of the model are tabulated in Table 3.1 below:

Properties	Value (units)
Water viscosity, μ_w	0.367 cP
Oil viscosity, μ_o	0.7 cP
Water density, ρ_w	63 lb/ft^3
Oil density, ρ_o	62.999 lb/ft^3
Water injection rate	8000 rb/day

Table 3-1: Fluid properties of Field X model

The above fluid properties are consistently used for simulation of the upgridding and upscaling activities.

CHAPTER 4: METHODOLOGY

There were two main activities in this study, namely upgridding and upscaling. Firstly, upgridding of the model was carried out to get the optimum layering scheme, which involve the lumping of cells in the vertical direction. This includes deciding which upgridding method yields the best result. Then, upscaling was performed based on the chosen layering scheme to average the dynamic properties of the coarsened model. In order to asses the efficiency of each upgridding and upscaling methods tested, the results are compared to the fine-grid simulation model. The findings and analysis of both exercises are then used to develop the FFR upscaling workflow. In all of the above activities, two two-dimensional (2-D) models were being used which are in the X- and Y-cross sections each.

Initially, the original Field X is a gas and oil reservoir. However, for simplicity and purpose of the study, the model is altered to be only an oil reservoir but the porosity and permeability distribution are maintained accordingly. In addition, due to some limitations of the software being used for the study, the inactive cells present are activated by changing the zero porosity cells with 1% porosity (smallest possible). Nevertheless, the fluids in place are not affected by the activation of the cells, thus the fluid flow is believed to be preserved accordingly.

4.1 Upgridding

For the upgridding exercise, two perpendicular cross-sectional models were constructed for the study. This was done to get a smaller representation of the fine-grid model, which would minimize its simulation run time. As long as the coarse model could reproduce the fine-grid cross sectional flow and saturation profile, it is believed to be capable of reproducing the full field model fluid flow. Quantitatively, the result of the cross-sectional fine-grid model will then be compared with the coarsened model where the difference between the two results will be quantified at a series of selected time steps as described in Section 5.1.

Apart from reducing the simulation run time, a 2D–model was chosen for the study as the rate effect near the injector wells is insignificant at certain condition. The rate effect can be controlled by changing the BHP of the injector wells as shown by Gillian et. al (2003) that changing the control of the injector well had little effect on the pseudos surrounding the injector well.

The dimensions of the two cross-sectional fine-grid models involved are shown in Table 4-1 below:

Cross section	X-direction	Y-direction	Z-direction
X	124	1	116
Y	1	96	116

Table 4-1: Dimensions of the cross-sectional model

The locations of the cross-sectional models were chosen to intersect at the crest. This is to ensure that the cross-sectional models are relatively located at the centre of the full field model. The locations of these cross-sectional models with respect to the static model are illustrated in Figure 4-1:

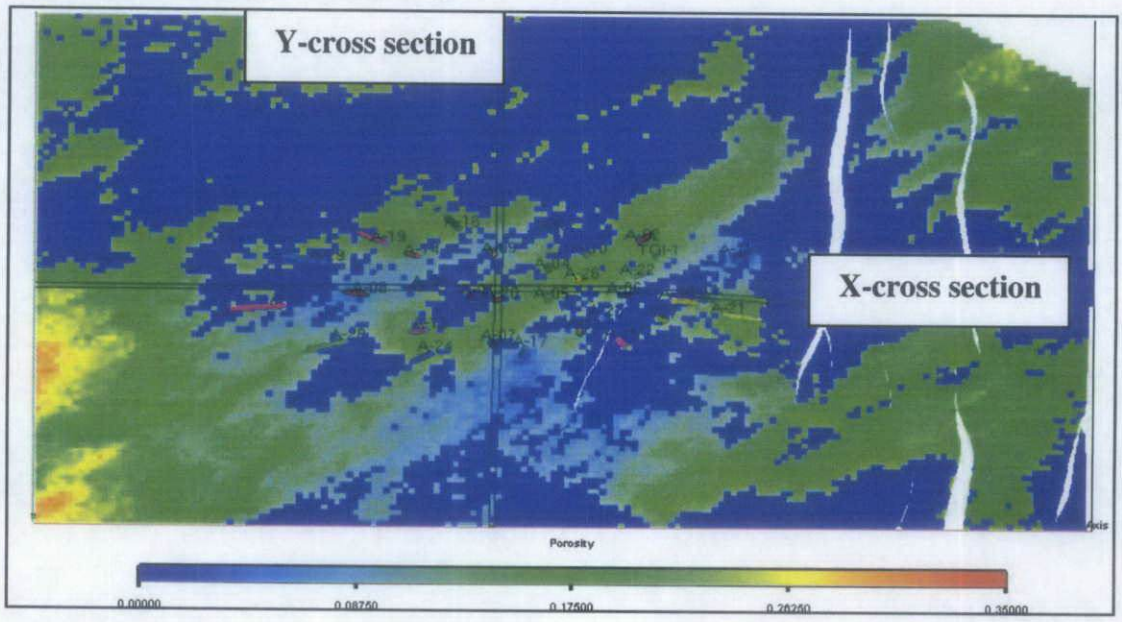

Figure 4-1: Cross-sectional model boundaries (areal view) of the fine-grid model.

For each of the cross-sectional model, a simple injection scenario was tested with the injection rate maintained at levels required to replace produced reservoir voidage at constant production rate. The two sets of simulation runs made for the fine-grid model and the coarsened model were as follows:

- X-direction cross-sectional model/water injection
- Y-direction cross-sectional model/water injection

The two models were tested for each set of the above to determine the optimum layering scheme for the simulation model. The methods involved are:

- Simple uniform layer method,
- Stern and Dawson method, and
- Variance in saturation (Darman et.al) method.

Note that the upgridding activities only focused on the vertical direction, which involved the lumping of cells in the z-axis of the model. No areal upgridding is considered as yet in this study which purposely designed to asses the impact of vertical upgridding of the fine-grid model.

The tests were conducted using P-Upscale application developed by PRSS. The user simply uploads the fine-grid model to be coarsened and select the upgridding methods to be used. The software is capable of calculating and determining the best coarse grid configuration that can maintain the accuracy of the fine-grid model. The interface of the application is shown below in Figure 4-2:

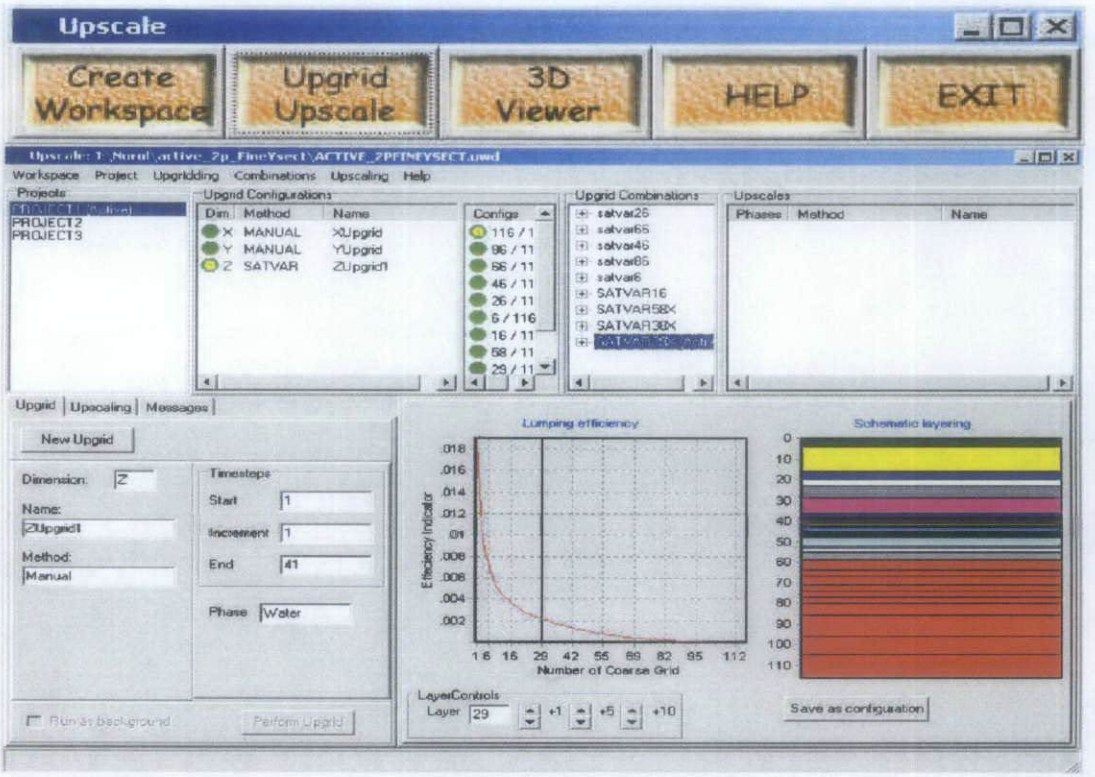

Figure 4-2: P-Upscale application interface used for testing the different upgridding methods.

The layering configurations given by P-Upscale for each upgridding methods are then evaluated in Eclipse application at a few selected layering scheme (26-, 29-, 38- and 58-layers). The error between the results of the fine-grid model and the coarse-grid model associated with the above methods are analysed based on its water-cut, oil rate and pressure profile as being carried out in Eclipse. The smaller the error, the closer the results with the fine-grid model and the better the method is.

4.2 Upscaling

For the upscaling activity, only the Y-cross sectional model was being used due to limited time available to continue with the X-cross sectional model. For the test, immiscible displacement of two-phase (water-oil) system was assumed. Thus, directional dynamic (pseudo-functions) upscaling methods were used to determine the relative permeability and capillary pressure curves. Using the optimum layering scheme obtained from the earlier upgridding exercise, the following methods were tested to upscale the dynamic properties of the simulation model:

- Rock curve
- Vertical Equilibrium
- Kyte and Berry
- Stone
- Hewett and Archer
- Transmissibility-weighted

The upscaling exercise was carried out based on the following conditions as the simulation input:

i. Permeability and porosity distribution were taken from the original field properties.
ii. A single relative permeability curve and capillary pressure was being used for simplification as described in Section 3.3.
iii. A producer located at the crest of the model.
iv. Two water injectors located at the far two ends of the model.
v. Full completion of producer and injectors.
vi. Directional, irreversible flow condition.

For error quantification, the variance between the results of the fine-grid model and the coarse-grid model associated with the above methods are analysed based on its oil rate, water-cut and pressure profile. The smaller the error, the closer the results with

the fine-grid model and the better the method is. The detail description of the error quantification technique is presented in Section 5.1.

Finally, please note that the detail description of the softwares used are beyond the scope of this paper. The methods used by the softwares involved have been described in Chapter 2 but the mechanism of the softwares will not be discussed.

CHAPTER 5: ANALYSIS OF RESULTS

5.1 Error Quantification

The performance of the different upgridding methods were evaluated based on the absolute average percent difference of the coarse-grid model compared to the fine-grid model. The average percent difference is taken from the percentage of the difference between the coarse and fine-grid model result at every time step over the fine-grid result and the summation is averaged over the number of time steps as given by the following formula:

$$Ave.\%\,difference = \frac{\sum_{i=1}^{n} \left| \frac{fine_i - coarse_i}{fine_i} \right|}{n}$$

Where $fine_i$ and $coarse_i$ are the fine and coarse-grid value at time step i and n is the total number of time steps. The smaller the average percent difference, the closer it is to the fine-grid model, thus the better the method is.

The parameters used for the error quantification purposes are the Field Oil Production Total (FOPT), Field Water Production Total (FWPT) and Field Pressure Rate (FPR) profiles for each case, as produced from Eclipse. The average percent difference was taken from the differences between the fine and coarse-grid model values at each time steps, for each profile.

For upgridding activities, the resulted average percent difference for each upgridding methods were presented in graphical form to compare the performance of each method at the different layering scheme selected (26-, 29-, 38- and 58-layers). As for the upscaling activities, the average percent difference computed for each method were tabulated according to the parameters stated earlier (FOPT, FWPT and FPR) for comparison and analysis.

5.2 Upgridding

As described earlier in Section 4.1, there are three upgridding methods involved in the analysis namely the simple uniform layer (UNI) method, Stern and Dawson (SD) method and variance in saturation (SATVAR) method. The fine-grid model was upgridded in the P-Upscale software developed by PRSS using the above mentioned methods. The 26-, 29-, 38- and 58-layering scheme generated by each methods are then being simulated in Eclipse to evaluate the efficiency of each method for the corresponding layering schemes. It is again mentioned here that the model is only upgridded in the vertical (z-axis) direction and not areally. Further study on the effect of areal upgridding is recommended as further work.

In this study, there are a number of observations made from the analysis of the three upgridding methods. Firstly, it is observed that the fine-grid (116-layers) model could be coarsened up to 29-layer vertically, reducing the number of cells from 11,136 to 2,784 for the Y-cross section, a 75% reduction in number of cells involved. This is shown in Figure 5-1 where the average percent difference for the FOPT and FWPT of the Y-cross section model at 29-layer scheme is about 2% for SATVAR and UNI methods. Even at 26-layers scheme, the SATVAR and UNI upgridding methods still could maintain the average percent difference to be around 2% error for the FOPT and FWPT. However, the average percent difference for the SD method started to increase at smaller number of layers and reached as high as 18% at 26-layer for the FOPT, 15% for FWPT and 5% for FPR.

This observation suggests that the SD method failed to capture the correct fractional flow at smaller layering scheme due to its failure in capturing the heterogeneities at certain parts of the model. For the 26-layer scheme, it is believed that the error in swept volume must have approaching its maximum at those parts of the model.

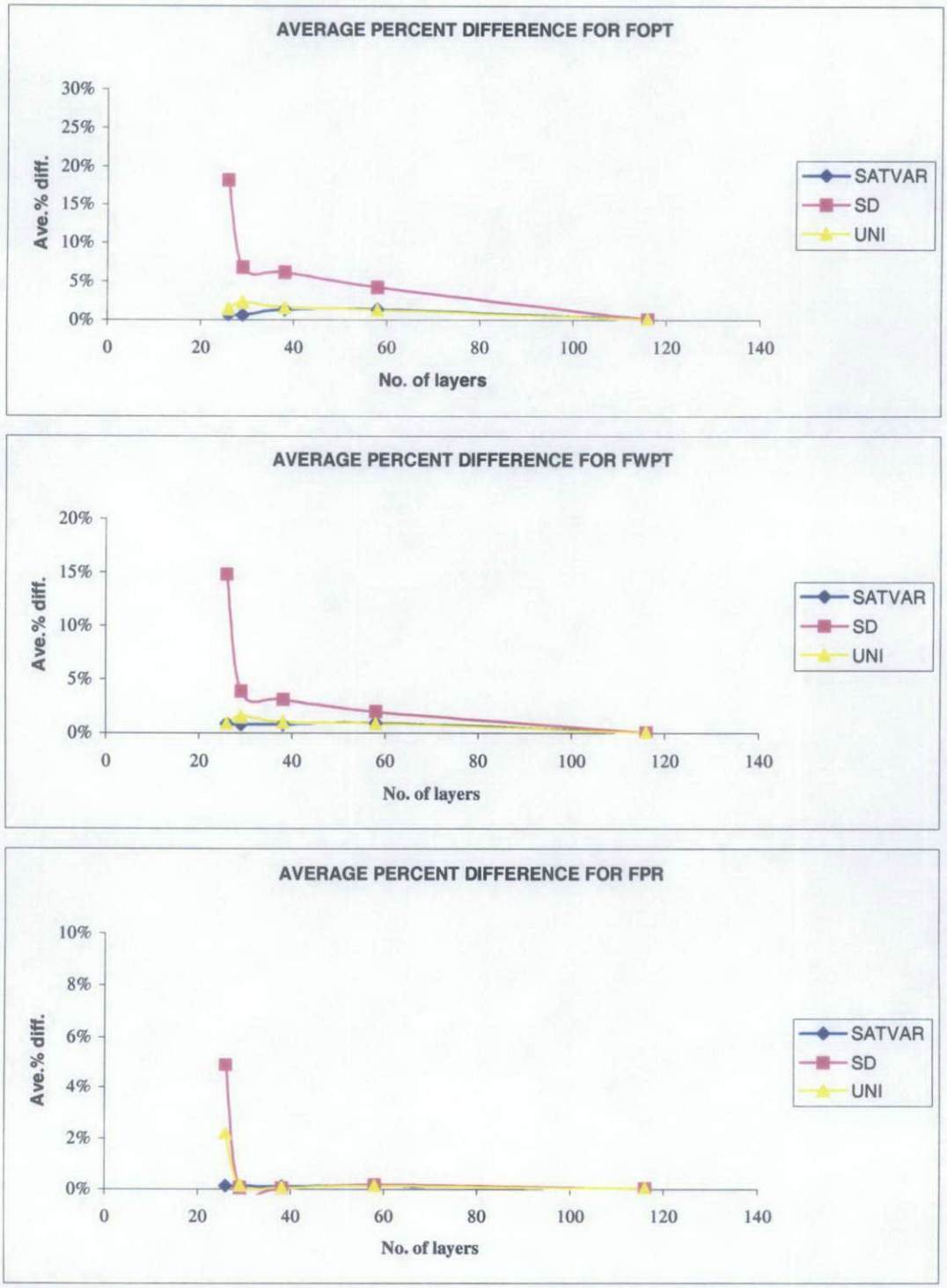

Figure 5-1: Average percent difference of Y-cross section for the different production profile.

Secondly, the coarsening scheme produced from the three methods had no significant effect on the pressure profile (PFR) at 29-layers and above. The FPR plots in Figure 5-1 show that all upgridding methods considered give a very small variation between the different layering schemes, less than 0.15% difference (±2.8 PSIA). However, it started to increase significantly at 26-layers for the SD method (5%) as well as the uniform layer method (2%). This value referring to 95 PSIA and 38 PSIA pressure difference at every time step as shown in Figure 5-2 below, which is considered high enough for the scale of 40 PSIA difference between the initial and final pressure of the fine-grid model. This indicates that for the reduced layering scheme, the uniform layer and SD method no longer captured the correct pressure profile, whereas the SATVAR method was still capable of handling the pressure distribution even for the reduced layering scheme or scheme with the fewest layers.

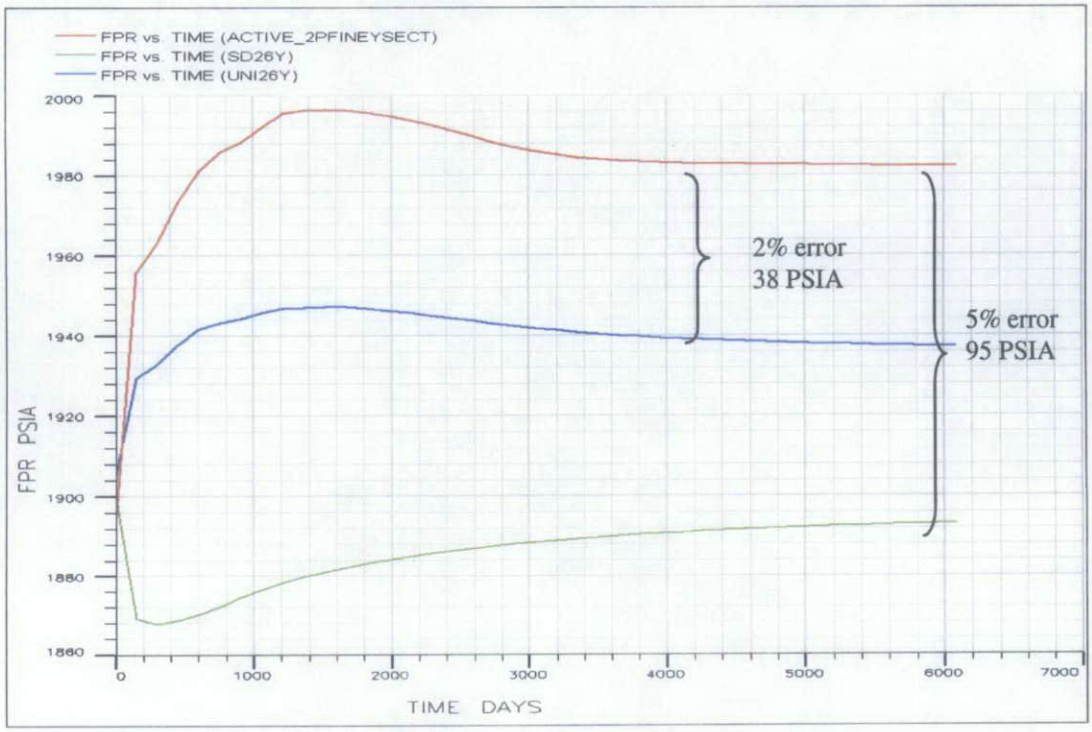

Figure 5-2: Pressure difference (error) between the 26-layers scheme of Uniform Layer method and Stern and Dawson method compared to the fine-grid model.

The above two observations imply that the 29-layers scheme is acceptable and sufficient to represent the fine-grid model. This will be used for the upscaling activities as the three methods successfully maintain an acceptable average percent difference at that layering scheme. This is further supported by the results obtained from the X-cross section model where the same trend is observed for the FOPT, FWPT and FPR but at different maximum values. The detailed average percent error for X-cross section is attached in Appendix B-I.

Next, the analysis on Figure 5-3 suggested that it was still possible to further reduce the number of layers using the variance in saturation and uniform layer layering scheme, depending on the allowable average percent difference for the model. For this particular field, a 2% error cut-off was being used. This 2% error is equivalent to 36,000 STB of FOPT and 198,000 STB of FWPT for the Y-cross section model, which are relatively acceptable compared to the original value of 1.8 MMSTB for FOPT and 9.9 MMSTB for FWPT.

At this 2% error cut-off, the variance in saturation method was the best method to be employed for this Field X as its highest average percent error was around 1.3% even for the 26-layer scheme. The method produced a good upgridding scheme as it considers the variability in saturation for its calculation. However, the Stern and Dawson method performed poorly compared to the other two methods as seen in Figure 5-3 where the 2% error cut-off is reached even at 58-layers scheme for all production profiles. This concluded that Stern and Dawson lumping scheme did not capture the heterogeneities of the field accordingly.

The same trend is also observed for the X-cross section model but a 3% cut-off error is assumed for this model which is equivalent to 189,000 STB of FOPT and 228,000 STB of FWPT compared to the fine-grid value of 6.3 MMSTB for FOPT and 7.6 MMSTB for FWPT. The plots of the X-cross section analysis are attached in Appendix B-II.

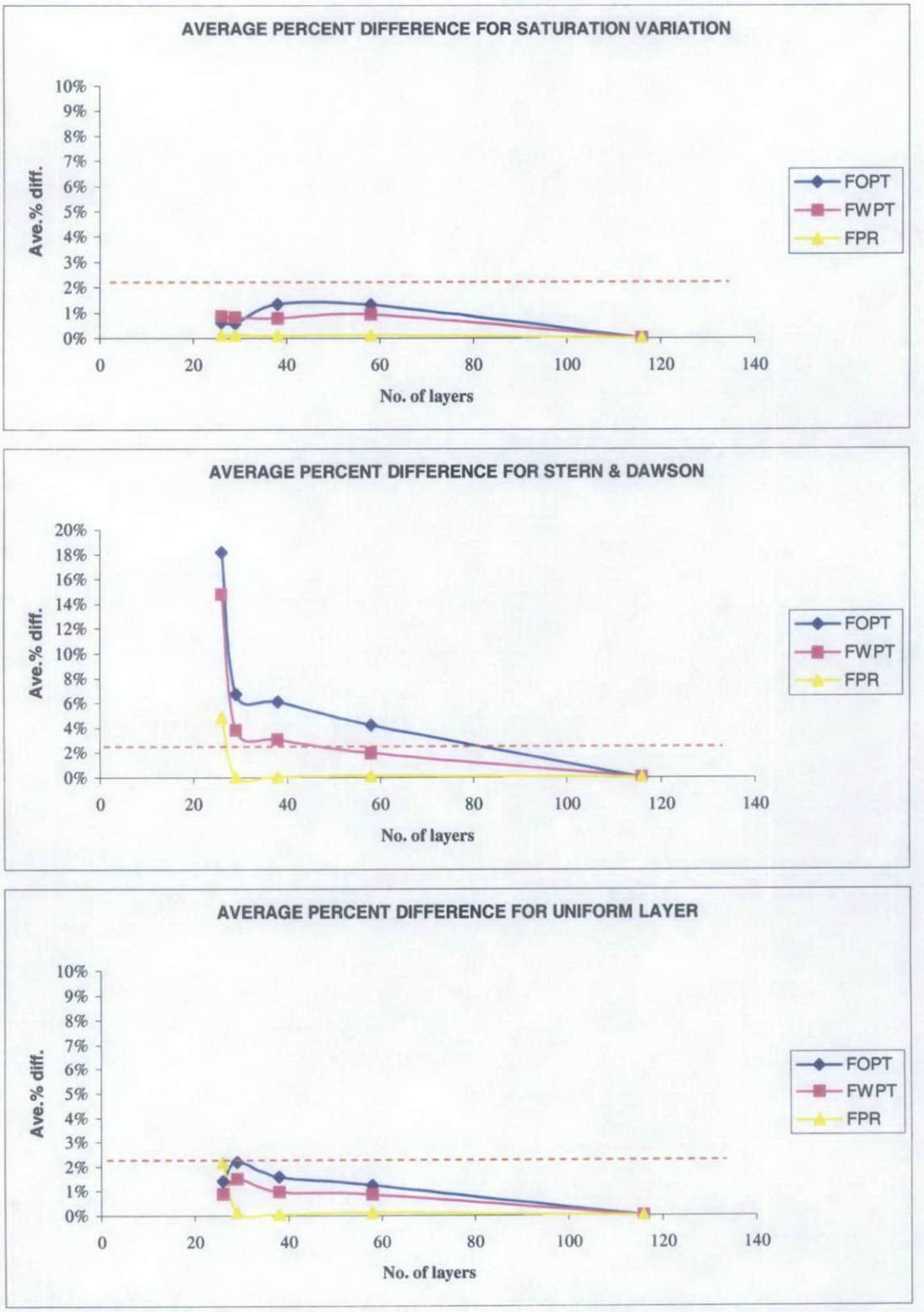

Figure 5.3- Average percent difference of Y-cross section for the different upgridding methods.

Apart from that, it was also found that the uniform layer lumping scheme is just as good as the variance in saturation method with 2.2% maximum error at 29-layers scheme as shown in Figure 5-3. The slight error decrease at 26-layers scheme might due to simulation convergence problems in Eclipse. Theoretically, this result was not expected at the beginning of the analysis as the uniform layers method is too simple to properly capture the correct fractional flow of the fine-grid model. As being mentioned in Section 2.1.1, theoretically, uniform layer method simply lump together the same numbers of layers through out the model without selectively choosing the critical area to be refine. The heterogeneities of the model might not be captured properly, thus affecting the flow of fluids in the reservoir.

However, for the Field X model, it happened that the reservoir was simple enough that the uniform layer method was sufficient to capture the heterogeneities accordingly. Figure 5-4 below illustrates the initial and final oil saturation of Field X (fine-grid Y-cross section model). It can be clearly seen that the lumping can be done based on the final oil saturation profile on the fine-grid where the layers with the same saturation can be lumped together.

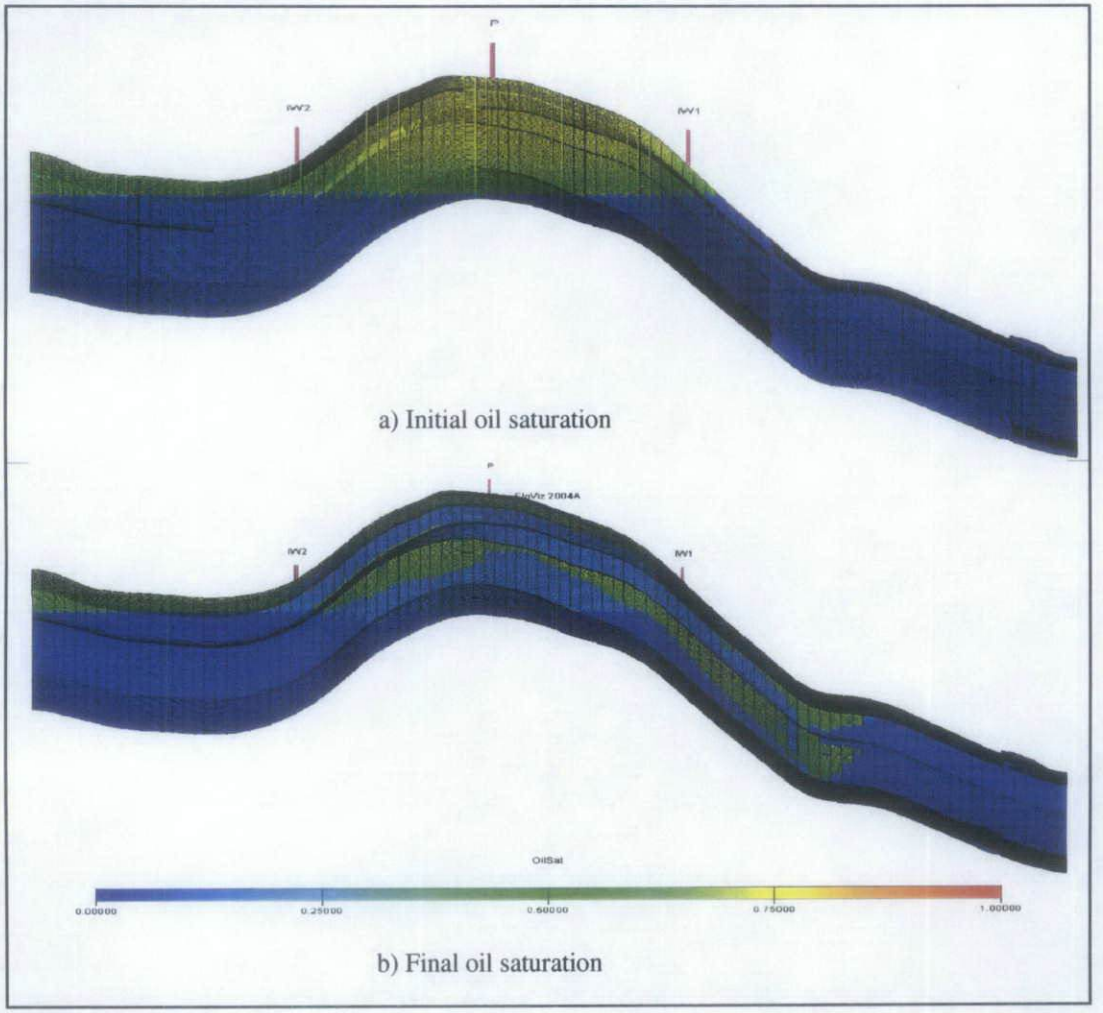

Figure 5-4: Oil saturation profile for Y-cross section fine-grid model.

For further information, Figure 5-5 illustrates the performance of the lumping scheme of the different upgridding methods. The variance in saturation and uniform layers methods have almost the same lumping pattern that results in an identical final oil saturation profile with the fine-grid model as in Figure 5-5. This explains the small error between the uniform layers upgridding method with the fine-grid model. The bigger error from Stern and Dawson method is resulted from the inefficient lumping scheme as shown in Figure 5-5 where the middle part of the model is too coarse, thus losing the fluid flow pattern in that section.

The same trend can also be seen in the X-cross section model in Appendix B-III and Appendix B-IV where the lumping of layers from variance in saturation method and uniform layers method are similar. The Stern and Dawson method lost some resolution of the oil saturation in the middle of the reservoir due to too much coarsening in that area.

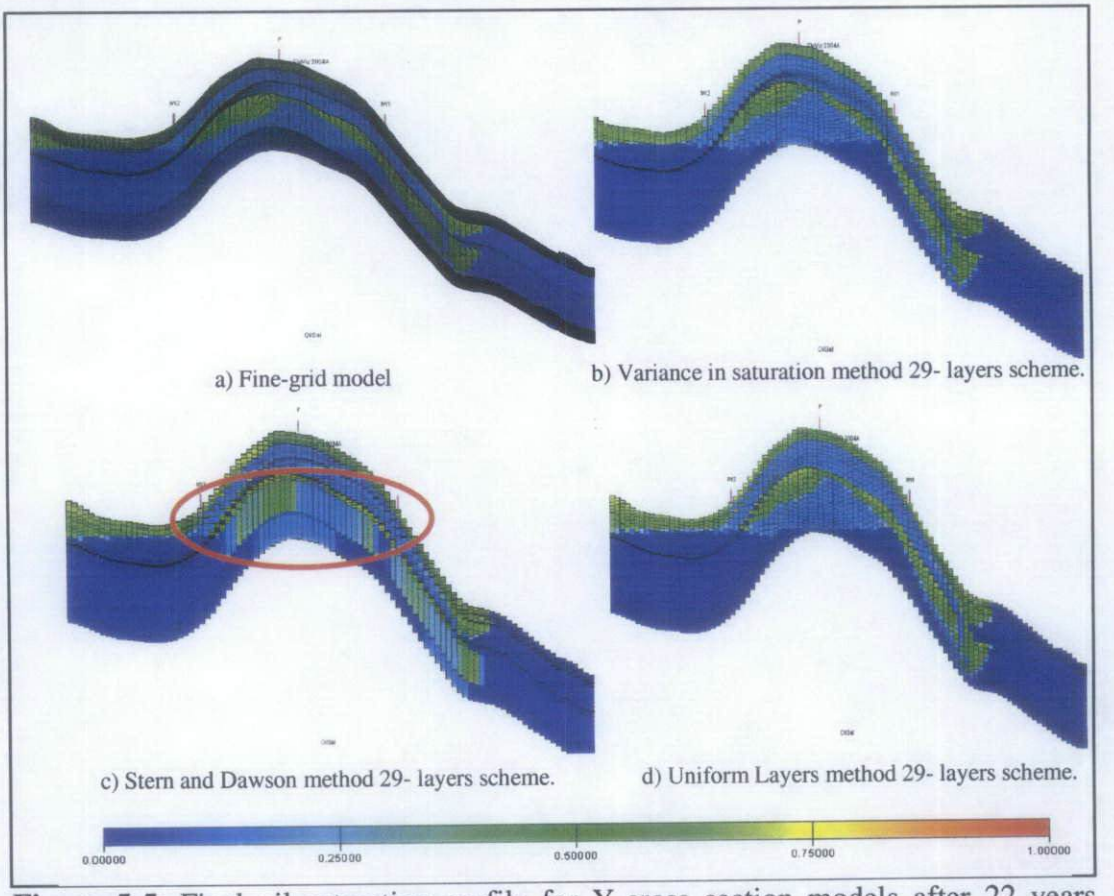

Figure 5-5: Final oil saturation profile for Y-cross section models after 22 years production.

From the above discussion on the upgridding activities, it can be summarised that the 29-layers scheme is sufficient to represent the fine-grid model and the variance in saturation method is the most suitable method to be used for Field X, where the layering can be further coarsened probably up to 20-layers scheme with that method. It is also observed that the Stern and Dawson method does not perform as good as the variance in saturation method and the uniform layers method happens to work according to preconceptions for the Field X model.

5.3 Upscaling

The upscaling activities were carried out based on the flow conditions described in Section 3.3 and Section 4.2. The simulation input is given in Appendix C. In the fine-grid model, the fluid flows were observed to be mainly in the horizontal direction as the gravity effect was minimised for the study by altering the fluid density of water and oil to be almost equal to each other. The fluids were seen to flow from the two ends of the model where the two injectors were placed towards the producer located at the crest. The upscaling activities were conducted only based on the Y-cross section of the fine-grid model due to the time constraint in completing the study, thus the X-cross section upscaling is left for further study on the subject.

As mentioned in Section 4.2, the methods involved for the upscaling study include rock curve (RC) method, Vertical Equilibrium (VE) method, Kyte and Berry (KB) method, Stone method, Hewett and Archer (HA) method and Transmissibility-weighted (TW) method. The upscaling for Y-cross section model was conducted on a 1x96x29 where only the z-direction layering was coarsened. The error quantification method is as described in Section 5.1, considering the same parameters as for the upgridding activities.

For the Field X model, the negligible density difference made the $\Delta\rho g\overline{\Delta h}$ term to be insignificant in averaging the fluid potential differences, even for a dipping model (Figure 5-6). Theoretically, it was anticipated that the TW and HA methods would give a closer match to the fine-grid model, followed by the KB method. The Stone method was expected to perform fairly good despite its neglect of gravity due to the negligible $\Delta\rho g\overline{\Delta h}$ term. Then, the VE method is not suitable at all as it is for low rates of areal fluid movement and the rock curve method might be as good as the other methods due to the single relative permeability curve used for the model.

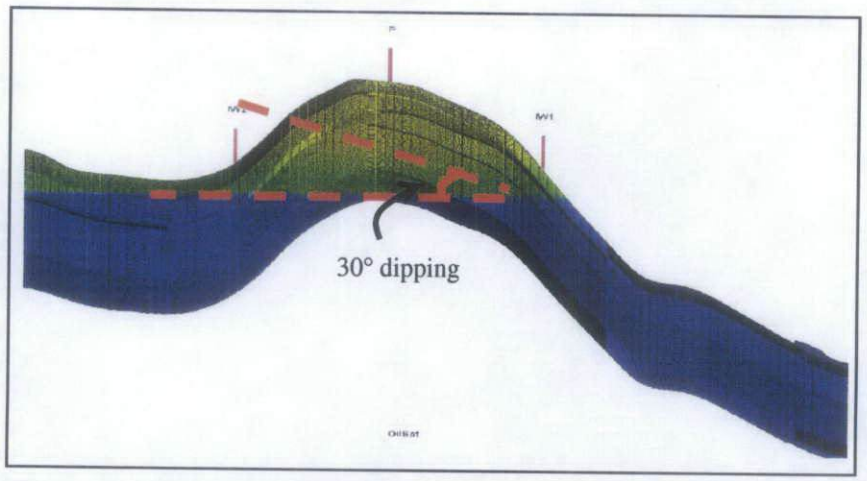

Figure 5-6: 30° dipping of the Y-cross section model.

The results of Y-cross section upscaling are summarized in Table 5-1 where the VE method gives the worst result and the Stone method gives the least error. For this model, the rock curve and TW methods both produced the same average percent difference, whereas the HA method has a slightly higher error compared to the last two.

METHODS	FIELD X		
	1 96 29		
	FOPT	FWPT	FPR
VE	176.4%	49.7%	2.5%
STONE	2.6%	0.8%	1.3%
KB	33.9%	10.9%	1.1%
RC	9.4%	2.3%	1.2%
TW	9.4%	2.3%	1.2%
HA	9.7%	2.4%	1.2%

Table 5-1: Y-cross section upscaling results.

As anticipated at the beginning of the upscaling procedure, the VE method would not perform well as it is only suitable for reservoirs with very low flow rates and only a modest degree of heterogeneity in either the vertical or horizontal dimension (Stone, 1991) which was reflected by the huge error from the results obtained. However, it was not expected that the Stone method to work better than the TW or HA methods.

The only reason explaining why the Stone method happened to work well for the model might due to the simplicity introduced into the model; a single relative permeability and capillary pressure curve used as well as negligible density difference.

The KB method had high average percent difference (33.9% FOPT, 10.9% FWPT and 1.1% FPR) as it assumed that the average fluids potential difference is set to be $\overline{\Delta\Phi_w} \neq \overline{\Delta\Phi_o}$, whereas the Field X model has $\overline{\Delta\Phi_w} = \overline{\Delta\Phi_o}$ due to negligible $\Delta\rho$ (Darman et. al, 2001). From Table 5-1, it can also be seen that the percentage error for the rock curve, TW and HA methods was very similar. It was expected that the TW and HA method would be equally good, but for this particular case, upscaling using the rock curves alone yield the same result as the pseudo functions. It is believed that the unexpected observation on the performance of the rock curve method was resulted from the highly simplified Field X model which used only a single relative permeability and capillary pressure curve. The fact that the Field X model is too simple had been proven by the sufficiently upgridded model using the simple uniform layer technique.

From the upscaling activities, it can be summarised that the VE method is not working for the Y-cross section model of Field X, the KB method performed worse than the Stone method and the TW method has the same results with the rock curve method.

CHAPTER 6: FULL FIELD REVIEW (FFR) APPLICATION

6.1 Current Practise

The geological model prepared by the geologist/geoscientist for the FFR team was always too large to be used directly for multiphase flow simulations. Thus, an appropriate upscaling procedure needed to be devised to honour the heterogeneity of the fine-grid model during the coarsening process. At present, there is no proper documented upscaling workflow in PETRONAS Research Sdn. Bhd. (PRSS) for its FFR teams to perform the simulation studies of the reviewed field. From interviews, the teams produce their dynamic models based on experience and the common practice of the previous FFR teams.

As mentioned earlier in Chapter 3, the Field X FFR team upgridded their static model from 1.8 million (169x96x116) grid cells to less than 75000 (85x40x22) grid cells. The optimum layering scheme was determined using the *variance in saturation technique* in the PRSS P-Upscale application. The static model properties (NTG, permeability, porosity, crititical water saturation (Swc) and residual oil saturation (Sor)) were upscaled using Schlumberger's FloGrid application which applies simple arithmetic averaging, linear boundary conditions, NTG weighted averaging and net pore volume averaging. The team believed that no pseudo-functions were necessary for the upscaling process. They believed that the coarse grid model preserves the static model properties reasonably well.

Another FFR team reduced their static model by half of its size areally for simulation. In contrast, the number of layers in the coarse grid model was set equal to those in the fine grid model as it is small enough to be simulated within an acceptable computational time. In fact, the highly stratified nature of the reservoir needs to be preserved in the coarse grid model in order to truly model its flow. The only property

that was upscaled was the porosity using the net pore volume averaging technique. The permeability, Swc and Sor of the coarse grid model were calculated using a correlation obtained from core data for each facies type. The team had the option of applying pseudo-functions for the upscaling purpose but had decided that the simple technique was sufficient to preserve the fluid flow.

It was observed that the use of pseudo-functions was not popular among the teams as its application is more complex than the simple technique. Proposing the use of dynamic pseudo-functions for upscaling the static model would be a great challenge.

6.2 A Practical Approach

The upscaling workflow developed in this thesis is based on some literature studies and the analysis described in the earlier chapters. The upgridding and upscaling studies conducted serve as a guideline in the selection of appropriate methods related to each activity, even though there is still a lack of understanding as to why a certain method will succeed in some cases but fail in the others.

Figure 6-1 below illustrates the simplified workflow suggested for upscaling the fine-grid geological (static) model into a coarser dynamic model, especially for PETRONAS FFR teams and any reservoir simulation projects:

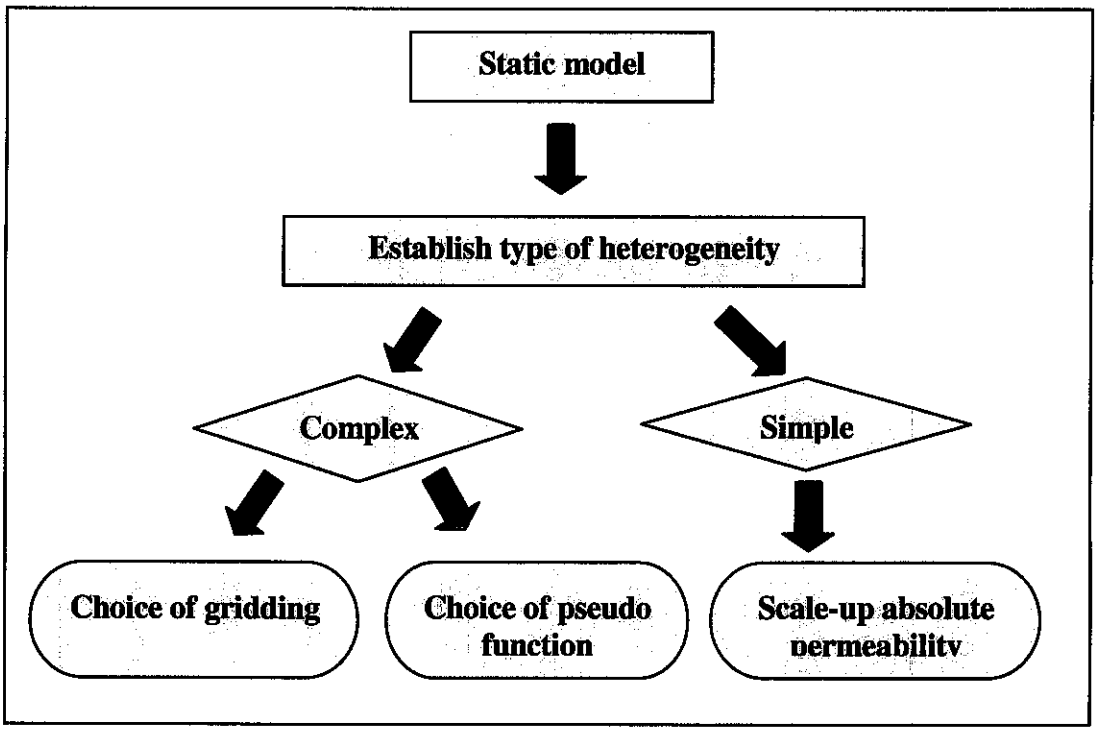

Figure 6-1: Proposed upscaling workflow for PETRONAS FFR teams and any reservoir simulation projects.

As a first step, the type of heterogeneity present in the static model needs to be established. This can be done by looking at the key features such as probable long, thin high-permeability channels; thin, high-permeability layers; and/or extended flow barriers, such as shales. If such features are not present, then the heterogeneity may have an insignificant effect on the flow and it may be sufficient to scale-up the absolute permeability alone. However, when the grid is too coarse, or if there are small-scale flow phenomena (viscous fingering or thin gravity tongues), pseudos may still be required to compensate for numerical dispersion.

However, if some of these geological features are present, a good upgridding choice is crucial. Coll et. al (1998) suggested that the coarse grid is selected based upon the spatial locations of the different force regimes operating in the fine grid simulation

model. To aid the engineers with the upgridding process, P-Upscale application developed by PETRONAS Research is useful for this purpose as it provides five published upgridding methods including the three methods tested in this report. The P-Upscale application is capable of upgridding the model areally and/or vertically depending on the user specification. The variance in saturation method is recommended based on its good performance as tested using Field X model but other methods might be useful on a different model. The layering scheme produced from Variance in Saturation method is accurate even at 25% of the original fine-grid model layering scheme. At this stage, it is worth considering the necessity of using a full-field model or whether a sector of the model could be used instead (such as cross-sectional model used in the study presented in this paper), depending on the objectives of the simulation study.

If there are too many of the previously mentioned geological features present, pseudo-relative permeabilities will be necessary apart from the upgridding exercise. There are two main reasons for using pseudo functions in reservoir simulation. Firstly, they can be used to capture the effect of interaction between multi–phase fluid flow and small-scale permeability variability and secondly, they can also be used to compensate for the effect of numerical dispersion in coarse grid models. Coll et. al (1998) pointed out that the pseudoisation method varies across the grid. The selection of the pseudoisation method is selected on the basis of the dominant force regime operating in that coarse grid block. In choosing the suitable pseudo-functions, it is necessary to check the whether the flow is gravity dominated (Vertical Equilibrium pseudos can be used), capillary dominated or viscous dominated. Darman et. al showed that the Stone, Transmissibility-weighted (TW) and Hewett and Archer (HA) methods all reproduce the correct fractional flows for purely horizontal model with negligible capillary pressure. For dipping models, the Stone method was very poor due to its neglect of gravity while the TW, HA and Kyte and Berry methods was not too different from each other (Darman et. al, 2001).

However, pseudos need to be regenerated every time the well rates or positions are changed significantly (Barker and Dupouy, 1996). In addition, if directional pseudos are used, it is important to decide on the flow orientation of the model, e.g whether it is directional and non-reversible, directional but reversible or directional in specific dimensions (x-, y- and/or z-). Darman et. al. have shown that although flow and pressure properties may be different in the x- and y- directions, the use of directional pseudo functions should guarantee the exact reproduction of the fine-grid results in the coarse-grid models as long as the pseudos are calculated independently in each of the directions.

It is also important to identify the rock types in the model where the coarse-gridblocks will be divided according to their internal heterogeneity and position in the reservoir. A set of pseudos should be generated for each rock type and any method used should verify that the coarse-grid model reproduce the fine-grid model results accordingly. If they do not match, the pseudos must be adjusted accordingly or a different method should be used which might be more suitable for the model.

Hopefully, with the existence of this workflow, the FFR team would benefit from it which works as a guideline for them in producing a reliable dynamic model. The team is free to further explore other options related to their upscaling procedures, provided that they understand the significance and contribution of the process towards creating a useful model. The accuracy of the dynamic model determines the quality of the project.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

1. For Field X model, a 29-layer scheme was sufficient to represent the fine-grid model resulting in a coarse grid-model with 1x96x29 gridblocks for the Y-cross section model and 124x1x29 gridblocks for the X-cross section model. At a 2% error cut-off, the variance in saturation method was the best method to be employed for this Field X and it was possible to further reduce the number of layers to 20. The method produces good coarse grid results. The Stern and Dawson method did not perform as good as the variance in saturation method. The uniform layer method works surprisingly well for the Field X model.

2. In upscaling the Y-cross section of the Field X model with , the VE method is not working at all, the KB method performed worse than the Stone method, the TW method has the same results with the rock curve method and the HA method has slightly a higher average percent difference compared to the last two.

3. The upscaling workflow developed serves as a guideline for the PETRONAS FFR team in constructing their dynamic model. Firstly, the team need to establish the type of heterogeneity presents in the static model. For a simple model, it is sufficient to scale up the absolute permeability alone. Whereas, for a complex model, the team should start with a good upgridding practice to determine the suitable number of gridblocks in their coarse-grid model. Then, the team should check for the dominant forces acting in the reservoir to determine the type of pseudos to be used.

All in all, it is concluded that the objective of developing a new upscaling workflow for the PETRONAS FFR team or other simulation project is met mainly referring on the literature reviews and supported by some of the findings of this paper. However, the study on the Field X model did not produces the anticipated results, especially on the upscaling activities.

7.2 Recommendations

For further works, it is recommended that a different pseudo function is applied to the different flow regimes in the model instead of using a single pseudoisation technique through out the whole model. Hopefully, the coarse grid model results will have a closer match with the fine grid model. The use of more than one relative permeability curves might make the study more challenging and able to distinguish the strength and limitation of each pseudo functions from the other. Other than that, it is highly recommended that the X-cross section upscaling of the Field X model to be resumed to further understand the behaviour of the reservoir. Finally, areal upgridding of the model is recommended on top of the vertical upgridding to further asses the reliability of the different upgridding methods.

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APPENDIX A

Literature Review

Appendix A

MILESTONES IN UPSCALING/UPGRIDDING STUDY

SPE Paper No.	Year	Title	Authors	Contribution
SPEJ DEC (1961)	1967	"Simulation of Three-Dimensional Two-Phase Flow in Oil and Gas Reservoirs"	K.H Coats, R.L Nielson, and M.H Terhune	First to introduce the "three-dimensional analysis" which employs a fully three-dimensional mathematical moc and "vertical equilibrium (VE) analysis" which only applicabl to reservoirs having good vertical communication.
SPEJ MAR (2797)	1971	"The Use of Vertical Equilibrium in Two-Dimension Simulation of Three-Dimensional Reservoir Performance"	K.H Coats, J.R Dempsey, and J.H Henderson	Illustrated the application of V concept in reservoir simulation model and its capability to simplify higher-dimension reservoir problem. This metho is useful for thick reservoir or for reservoir with capillary transition zone that is a small fraction of its thickness.
SPEJ AUG (5105)	1975	"New Pseudo Functions to Control Numerical Dispersion"	J.R Kyte and D.W Berry	Improved the calculation of dynamic pseudo functions in two-dimensional simulation compared to the earlier published approaches.
21207	1991	"Rigorous Black Oil Pseudo Functions"	H.L Stone	First to introduce Stone metho which calculates black oil pseudo functions from a fine grid simulation of a reservoir, especially for waterflood syste
37988	1997	"Scale-Averaged Effective Flow Properties for Coarse-Grid Reservoir Simulation"	T.A Hewett and R.A Archer	First to introduce unambiguou rules for computing effective flow properties for coarse grid simulations, especially for waterflood system.
51941	1999	"The Development of Pseudo Functions for Gravity-Dominated Immiscible Gas Displacements"	N.H. Darman, K.S Sorbie and G.E Pickup	First to introduce Transmissibility-Potential-Weighted (TPW) method especially for gas-oil system.

51942	1999	"A Technique for Generating Reservoir Simulation Grids to Preserve Geologic Heterogeneity"	D. Stern and A.G Dawson	Introduced improved techniqu to preserve geologic heterogeneity of the fine grid model in the coarse grid mode
66377	2001	"The Calculation of Pseudo Functions Using Potential Averaging Methods"	N.H Darman, K.S Sorbie and G.E Pickup	Compared the performance of the different dynamic upscalin methods.

Appendix A

LITERATURE REVIEW SUMMARY

SPEJ DECEMBER (1967)

Simulation of Three-Dimensional Two-Phase Flow in Oil and Gas Reservoirs

Authors: K.H Coats, R.L Nielson, and M.H Terhune, A.G Weber

Contribution to the understanding of upscaling model:

Introduction to "three-dimensional analysis" which employs a fully three-dimensional mathematical model and "vertical equilibrium (VE) analysis" which only applicable to reservoirs having good vertical communication.

Objective of the paper:

To introduce two computer-aided techniques for simulating the three-dimensional flow behaviour of two-phase fluid reservoir.

Methodology used:

Treated both fluids as incompressible and accounting the effects of relative permeability, capillary pressure and gravity in addition to reservoir geometry and rock heterogeneity.

Conclusion reached:

1. The validity of three-dimensional analysis was indicated by experimental data.
2. VE analysis is applicable for simulating three-dimensional flow behaviour in reservoirs having good vertical communication.
3. The VE criterion parameter provides quantitative test for determining whether a reservoir can be modelled reliably using the VE analysis.
4. If VE analysis is applicable, it should be used in preference to the three-dimensional analysis.

Comments:

This method is useful for reservoir model with large areal extent relative to its thickness and when viscous force is negligible.

SPEJ MARCH (1971)

The Use of Vertical Equilibrium in Two-Dimension Simulation of Three-Dimensional Reservoir Performance

Authors: K.H Coats, J.R Dempsey, and J.H Henderson

Contribution to the understanding of upscaling model:

Understanding on the application of VE concept in reservoir simulation model and its capability to simplify higher-dimension reservoir problem. This method is useful for thick reservoir or for reservoir with capillary transition zone that is a small fraction of its thickness.

Objective of the paper:

To discuss the use of the vertical equilibrium (VE) concept in simulating heterogeneous reservoirs, and to present a new dimensionless group of a possible criterion for the validity of VE application.

Methodology used:

Assumed fluid gravity segregation to generate pseudo capillary pressure and relative permeability curves using VE concept introduced by Coats et. al.(1967).

Conclusion reached:

1. When VE concept is applicable, man-time and machine-time are saved. The 2-D areal calculations duplicate the more complex 3-D calculations.
2. A new dimensionless group, G was derived to be a possible priori check on the validity of the VE assumption for small transition zone systems.
3. The VE concept is capable of solving a higher dimension reservoir problem using a smaller-dimension model.

Comments:

The VE concept is applicable to gas-oil, water-oil, gas-water or three-phase system. However, this paper discussed its application on a gas-water system.

SPEJ AUGUST (1975)

New Pseudo Functions to Control Numerical Dispersion

Authors: J.R Kyte and D.W Berry

Contribution to the understanding of upscaling model:

Introduction to Kyte and Berry method which is an improvement in calculating dynamic pseudo functions in two-dimensional simulation compared to the earlier published approaches.

Objective of the paper:

1. To present an improved procedure for calculating dynamic pseudo functions that may be used in two-dimensional areal reservoir simulations to approximate three-dimensional reservoir behaviours.
2. To demonstrate that the new procedure generally is more applicable than any previously published approaches.

Methodology used:

Accounts for the differences in computing block lengths between the areal and cross-sectional models.

Conclusion reached:

1. The new procedures for calculating dynamic pseudo functions are more widely applicable compared to the previous published approaches and may be applied to wide range of flow conditions.
2. Application of the new pseudos saved both time and money.

Comments:

The pseudo functions generated by this method do not prevent some losses in areal flow-pattern definition when the number of computing blocks in the two-dimensional areal model is reduced.

SPE 21207 (1991)

Rigorous Black Oil Pseudo Functions

Authors: H.L Stone

Contribution to the understanding of upscaling model:

Introduction to Stone method which calculates black oil pseudo functions from a fine grid simulation of a reservoir, especially for waterflood system.

Objective of the paper:

4. To discuss the methodology, assumptions and limitations of the method, including Jacks et.al and Kyte & Berry methods.
5. To compare and evaluate the effectiveness of the models.

Methodology used:

Made the coarse grid fractional flow a total flow rate weighted average of the fine grid fractions and used Kyte and Berry's method to calculate the corresponding saturations.

Conclusion reached:

3. The Stone method is rigorous for all flow rates, even for non communicating layers where the viscous to gravity ratio is infinite.
4. Jacks et. al method is accurate only for low viscous-gravity ratios and the Kyte & Berry is not generally viable because of its incorrect assumption.
5. Maximum accuracy will be achieved if the full-field block in which pseudos are used and the idealized coarse grid block from which they were derived have approximately the same reservoir properties, initial conditions and total flow velocity vector as a function of time.

Comments:

This method is very useful, reliable and effective for the coarse grid idealized model at all flow rates even for totally non-communicating layers.

SPE 37988 (1997)

Scale-Averaged Effective Flow Properties for Coarse-Grid Reservoir Simulation

Authors: T.A Hewett and R.A Archer

Contribution to the understanding of upscaling model:

Introduction to unambiguous rules for computing effective flow properties for coarse grid simulations, especially for waterflood system.

Objective of the paper:

To define scale-averaged properties for use in coarse grid reservoir simulations, which considered the effects of fine-scale permeability variations in the fine grid model.

Methodology used:

Conceptually computing the individual phase mobilities in streamtube segments whose geometry is defined by the fine grid cells at the coarse grid block outlet face.

Conclusion reached:

1. The potential differences used in calculating the integrated phase mobilities between coarse grid block centers are taken constant and not weighted averages of the potentials obtained from the fine grid solution.
2. The resulting averaging rules are different compared to the previous methods when effective capillary pressure and gravity term are added.

Comments:

This paper addressed the modifications required in the Hewett and Yamada method to include the effects of gravity and capillary pressure in the definition of effective flow properties for coarse grid.

SPE 51941 (1999)

The Development of Pseudo Functions for Gravity-Dominated Immiscible Gas Displacements

Authors: N. H. Darman, K.S Sorbie and G.E Pickup

Contribution to the understanding of upscaling model:

Introduction to Transmissibility-Potential-Weighted (TPW) method which will be tested in the project.

Objective of the paper:

3. Propose TPW method that has been developed to handle cases with significant effect of gravity in the simulation models.
4. Investigate the best conditions that the method performs better than the existing approaches.
5. Propose a new coarsening scheme that reduces the error in duplicating the fine grid model performance.

Methodology used:

The new TPW method followed the approach of Kyte & Berry except in the averaging the fluid potential difference at the coarse grid level.

Conclusion reached:

1. TPW method gives more accurate results in applying pseudo functions where gravity effects are significant compared to the Kyte & Berry, Stone and VE methods.
2. The difference between TPW and Kyte & Berry methods is the weighting factors used in the pseudo equations where the relative permeability weighting used in the Kyte & Berry method is particularly inappropriate in cases where gravitational effects are significant.
3. TPW gives accurate upscaled answers if the fine grid accurately reproduced the reservoir flows which may be viscous dominated, gravity dominated or in a flow regime where all forces are significant.

4. The error in applying the TPW equation in grid coarsening scheme can be reduced if the regions (layers) within which the variability in gas saturation is as low as possible, is separated.

Comments:

This method is especially used in immiscible two phase displacement in oil-gas systems whereas the project is mainly for water-oil system. However, the performance of TPW would still be investigated for the water-oil system.

SPE 51942 (1999)

A Technique for Generating Reservoir Simulation Grids to Preserve Geologic Heterogeneity.

Authors: D. Stern and A.G Dawson

Contribution to the understanding of upscaling model:

Further understanding on the techniques and steps to preserve geologic heterogeneity of the fine grid model in the coarse grid model.

Objective of the paper:

To describe a technique for optimally selecting simulation model layers to preserve the heterogeneity in the geologic model.

Methodology used:

Focused on selecting layering, since permeability contrast and degree of coarsening is usually higher in vertical direction than areally.

Conclusion reached:

1. The approach produced models that are as accurate or better than those by conventional means especially when the geologic model contains heterogeneity that correlates over distances compared to displacement length.
2. Suitable for multiphase simulation studies and is straightforward to be applied to multi-million cell geologic models.
3. Allows relatively simple determination of the number of layers required to preserve vertical heterogeneity.
4. Improved early-time accuracy of the coarse grid model.

Comments:

The technique introduced is easy to follow and efficient enough where applicable.

SPE 66377 (2001)

The Calculation of Pseudo Functions Using Potential Averaging Methods.

Authors: N.H Darman, K.S Sorbie and G.E Pickup

Contribution to the understanding of upscaling model:

Performance comparison of the different dynamic upscaling methods.

Objective of the paper:

To describe the results of an assessment of Kyte & Berry method, The Stone method, the Hewett & Archer method and the Tansmissibility-Weighted (TW) method.

Methodology used:

Investigated the need to preserve fractional flow in the coarse grid model and the requirement to preserve fluid mobility and pressure distribution between the fine and coarse grid model.

Conclusion reached:

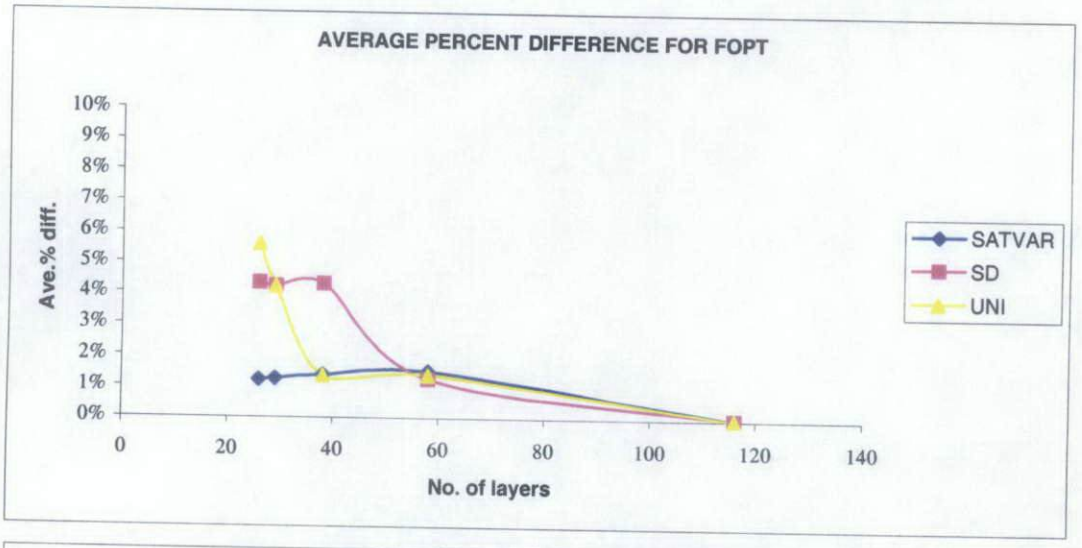
1. The Stone, TW and HA methods lead to the same (correct) fraction flows for purely horizontal models with negligible capillary pressure.
2. For dipping models, TW, HA and KB methods gave slightly different answers but the Stone method was very poor due to its neglect of gravity.

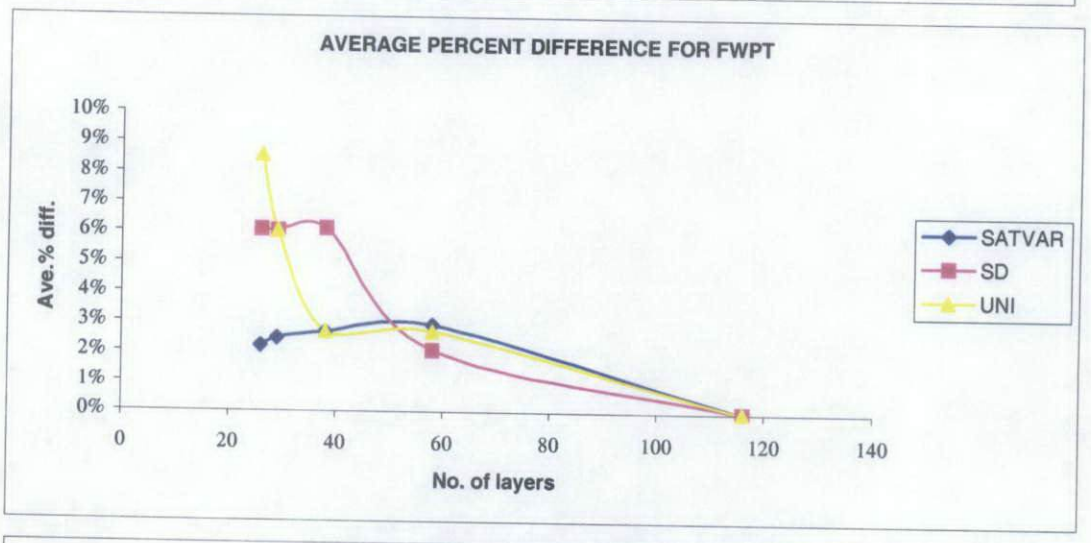
Comments:

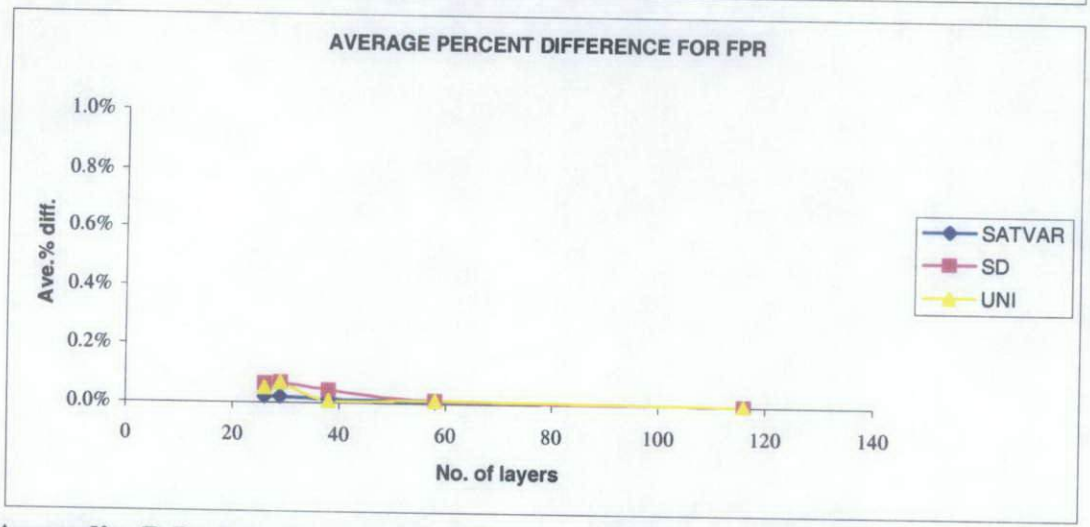
The analysis was done assuming oil and gas flow, but the authors claimed that their findings are also true for waterflooding.

APPENDIX B

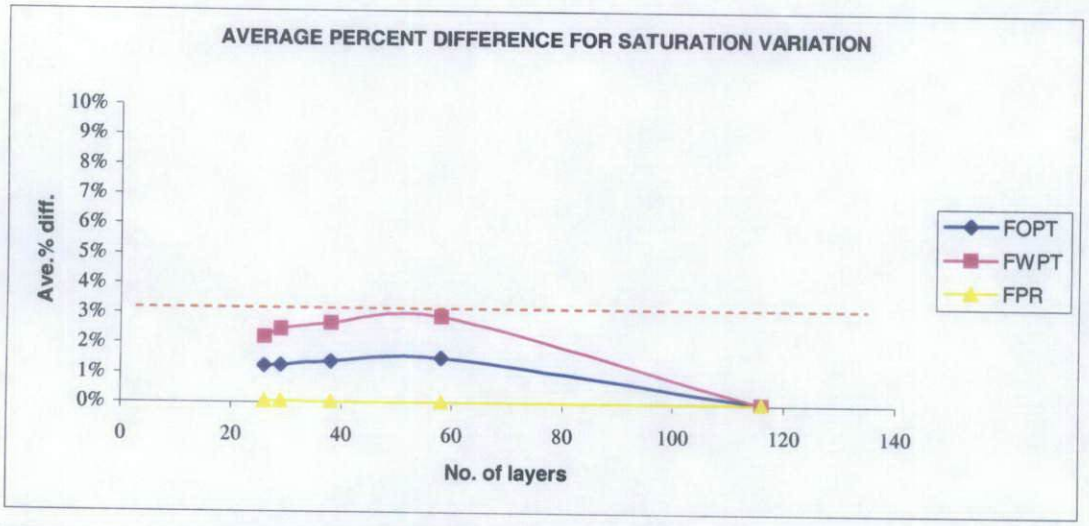
Analysis of Results

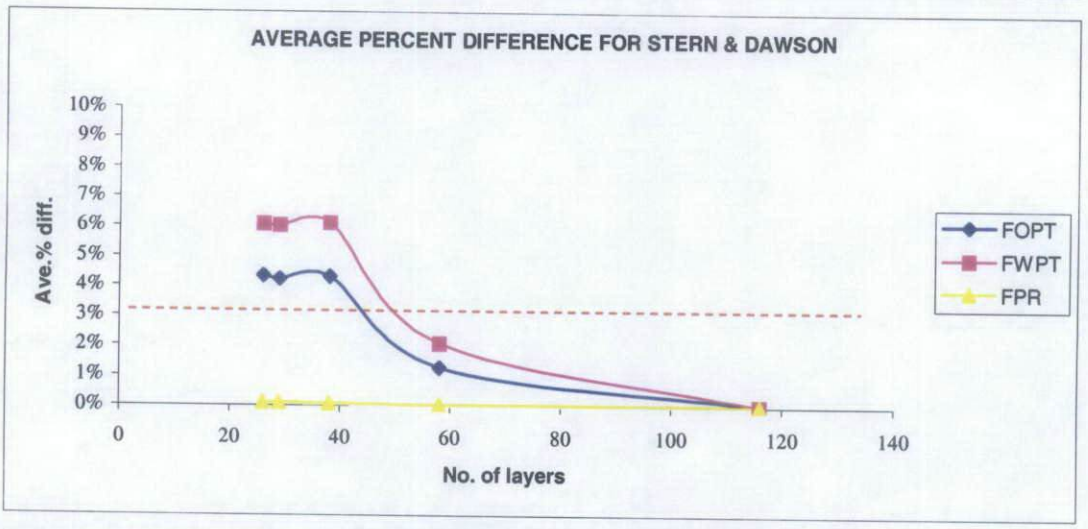


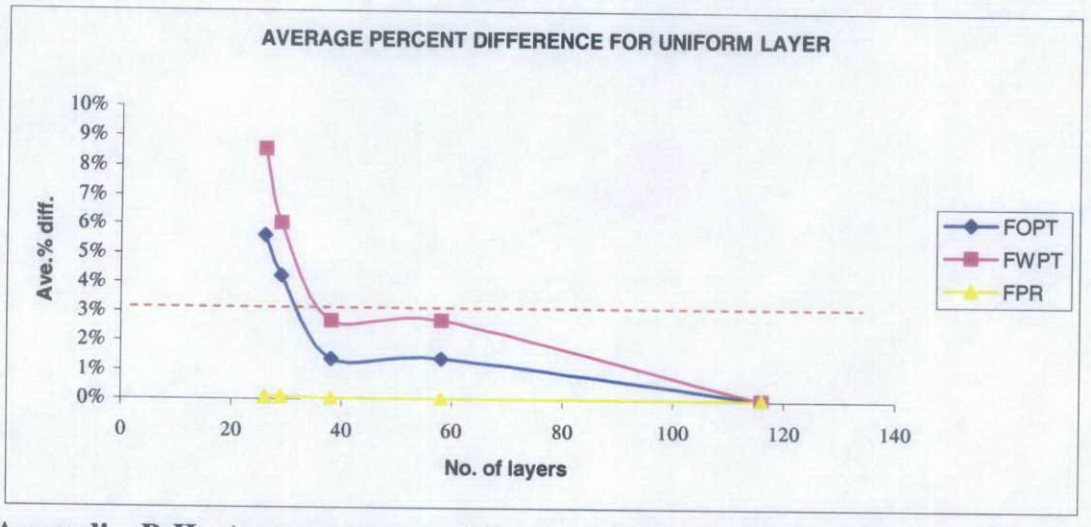




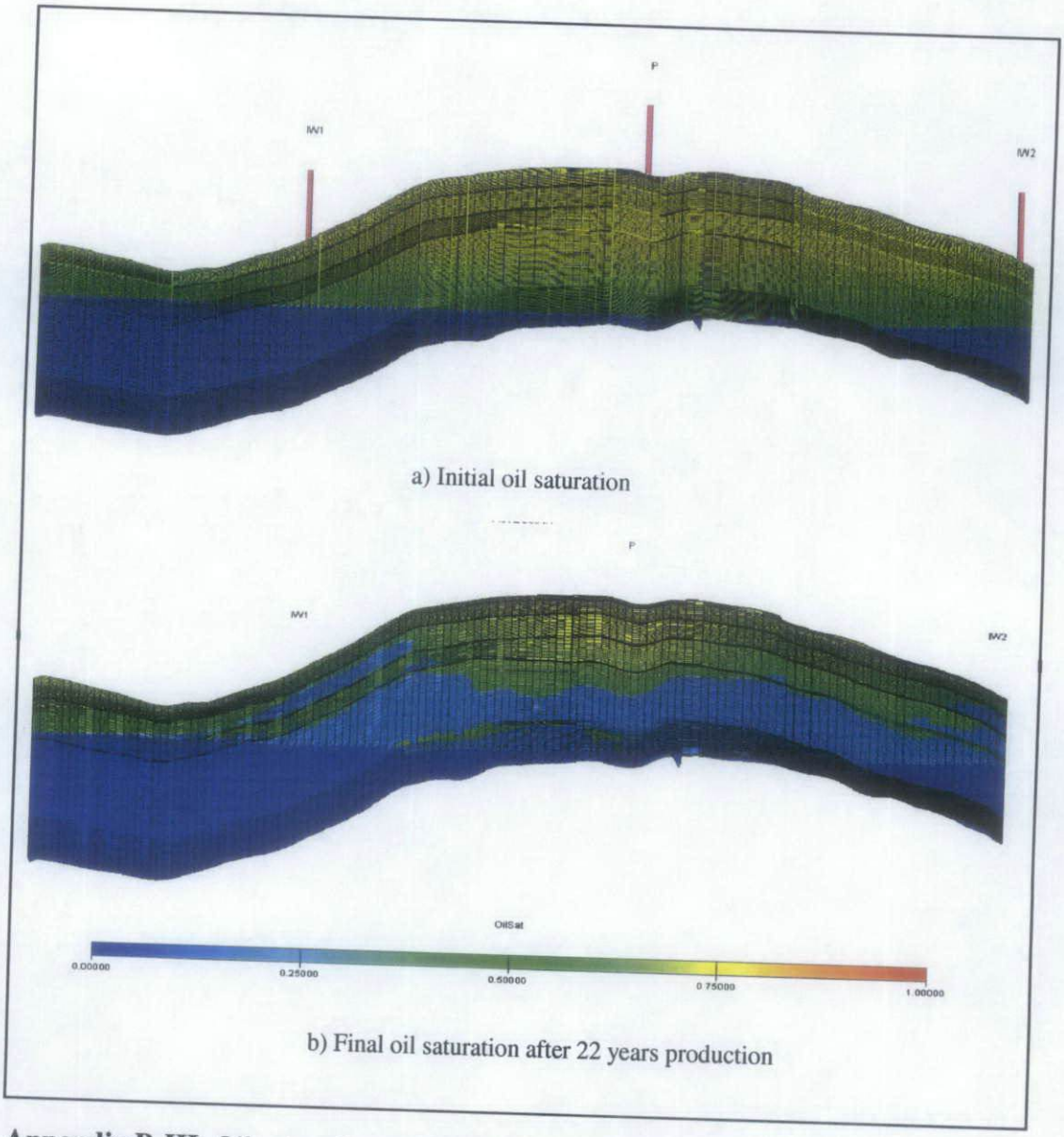
Appendix B-I: Average percent difference of X-cross section for the different production profile.



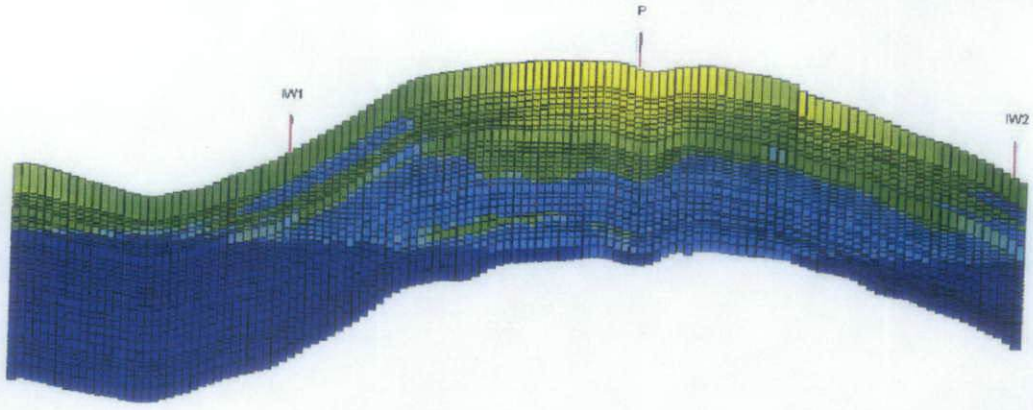




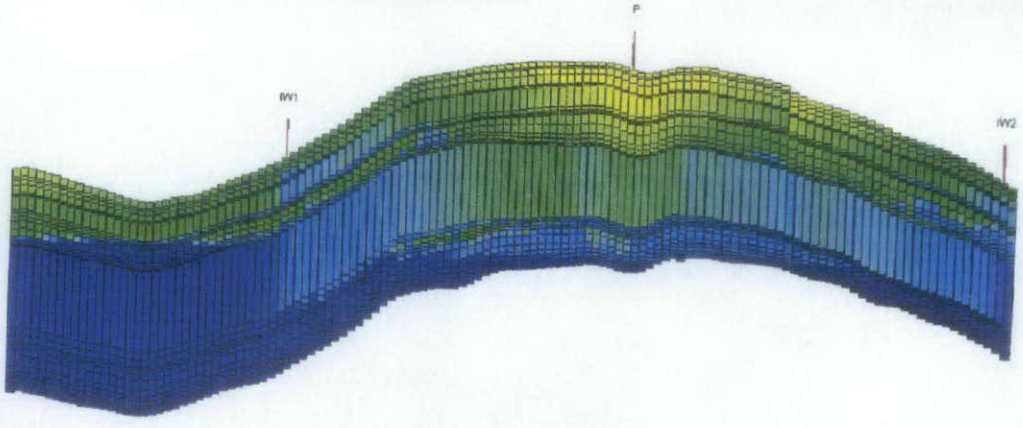
Appendix B-II: Average percent difference of X-cross section for the different upgridding methods.



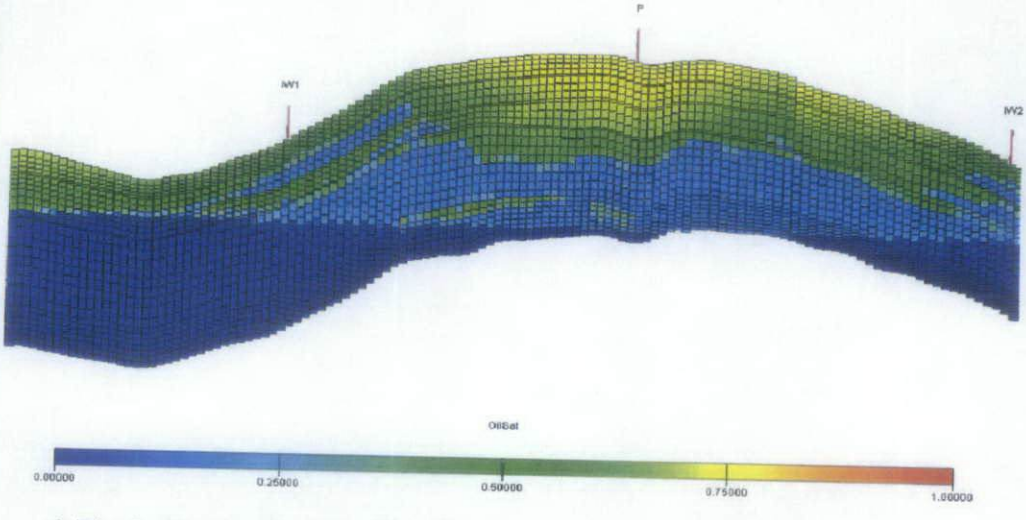
Appendix B-III: Oil saturation profile for X-cross section fine-grid model.



a) Final oil saturation profile after 22 years production for Variance in Saturation method 29- layers scheme



b) Final oil saturation profile after 22 years production for Stern and Dawson method 29-layers scheme.



c) Final oil saturation profile after 22 years production for Uniform Layers

Appendix B-IV: Oil saturation profile for X-cross section coarse-grid model.

APPENDIX C

Simulation Inputs

SIMULATION INPUT FILES

```
RUNSPEC

TITLE
FINE GRID FULL FIELD MODEL OF J-RESERVOIRS AT FULL GEOMODEL RESOLUTION

NOECHO

DIMENS
  1  96  116 /

OIL

WATER

FIELD

EQLDIMS
   1  100   10    1   20 /

SATOPTS
DIRECT IRREVERS /

TABDIMS
   1    1   16   50    3   20 /

WELLDIMS
-- MAXWEL MAXCON MAXGRP MAXWGP
   5    120    1      5 /

START
 1 'NOV' 1982  /

NSTACK
  20 /

UNIFIN
UNIFOUT

GRID  ========================================================================

MESSAGES
9* 10000 /

INIT

INCLUDE
'FINEXSECTY.GRDECL'
/

COPY
PERMY PERMX /
PERMY PERMZ /
```

```
/

MULTIPLY
PERMZ 0.00 /
/

RPTGRID
'TRANX' 'TRANY' 'TRANZ' /

PROPS
================================================================
-------- THE PROPS SECTION DEFINES THE REL. PERMEABILITIES, CAPILLARY
-------- PRESSURES, AND THE PVT PROPERTIES OF THE RESERVOIR FLUIDS
----------------------------------------------------------------

-- PVT PROPERTIES OF WATER
--
--   REF. PRES. REF. FVF  COMPRESSIBILITY  REF VISCOSITY  VISCOSIBILITY

PVTW
    1900    1.036      3.07E-6        0.367         0 /

PVCDO
    1900        1.065       1.6e-5             0.7          0 /

-- ROCK COMPRESSIBILITY
--
--   REF. PRES   COMPRESSIBILITY

ROCK
     1900       3.0e-6       /

DENSITY
        62.99999        63       0.07    /

INCLUDE
'RELPERM_denorm.INC'
/

REGIONS ========================================================

EQUALS
SATNUM  1  4*  1 116 / -- J15 + J15.5
FIPNUM  1  4*  1 36 / -- J15 + J15.5 + J16
FIPNUM  2  4* 37 52 / -- J18
FIPNUM  3  4* 53 116 / -- J19 + J20
/

SOLUTION ======================================================

EQUIL
--    Datum   Datum    OWC    OWC   GoC    GoC  Rsvd
--    Depth   Pressure Depth  Pcow  Depth  Pcog Table
     4300    1903     4393    0    4000   0     0   /

RPTSOL
```

```
  0  0  0  0  0   0  1  2  0  0   0  0  0  0  0
  0  0  0  0  0   0  0  0  0  0   0  0  0  0  0
  0  0  0  0  0   0  0  0  0  0   0  0  0  0  0
  0  0  0  0  0   0  0  0  0  0   0  0  0  0  0
/

RPTRST
ALLPROPS=2  BASIC=5   FREQ=2 DEN FIP FLOWS PCOW, PCOG, POT PRES /

SUMMARY =====================================================
RPTONLY
FOPR
FWPR
FGPR
FVPR
FWIR
FGIR
FVIR
FWCT
FGOR
FOPT
FWPT
FGPT
FVPT
FWIT
FGIT
FVIT
FPR
FPPO
WOPR
/
WVIR
/
WWIR
/

RUNSUM
SEPARATE

SCHEDULE ====================================================

RPTSCHED
'FIP=1' 'RESTART=2' /

TUNING
/
/
2* 40 1* 16 /

WELSPECS
'IW1' 'G'  1  33   1*  'WAT'  /
'P'   'G'  1  54   1*  'OIL'  /
'IW2' 'G'  1  80   1*  'WAT'  /
/
```

```
COMPDAT
'P      '  2*  1  82 'OPEN'  0  .0   0.5 / -- J1920FS (9)
'IW*    '  2*  1  116 'OPEN'  0  .0   0.5 / -- J15SB (2) - J18SB (8)
/

WCONPROD
'P' 'OPEN' 'RESV' 4* 2000.0 800.0 /
/

WCONINJE
'IW*' 'WATER' 'OPEN' 'GRUP' 2*  8000.0 /
/

GCONINJE
--Group  Inj  CTL
--Name   Phase
 FIELD  WATER  VREP  3*  1 /
/

WGRUPCON
'IW*' Y  100  RES /
/

TSTEP
1  1.194  1.425636  1.702209384  2.032438004  2.426730977  2.897516787
3.459635044  4.130804242  4.932180265  5.889023237 7.031493744
8.395603531  10.02435062  11.96907464  14.29107511  17.06354369
20.37387116  24.32640217  29.04572419  34.68059468  41.40863005
49.44190428  59.03363371  70.48615865  84.16047342  100.4876053
119.9822007  143.2587476  171.0509447  204.2348279  243.8563845
291.1645231  347.6504406  415.0946261  495.6229836  591.7738424
706.5779678  843.6540936  1007.322988
/
END  ============================================================
```

Appendix C-I: Y-cross section (fine-grid) data file